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CORRECTIONS AND EMENDATIONS

Contributors to Volume 48 have been invited to send corrections and emendations to be made in their paper, and the volume has been scanned with some care. Corrections and insertions are as follows:

Page 77, line 3 from bottom, *complete* $\sqrt{\ }$ sign over κ.

" 85, equation at top should read $\frac{\partial v}{\partial x} = m + \frac{v_s}{\sqrt{\pi \kappa t}} e^{-\frac{x^2}{4\kappa t}}$

" 85, line 10, *change* style of κ to conform with others.

" 86, line 12, *complete* $\sqrt{\ }$ sign over κ.

" 89, line 12 from bottom, *for* 1°C. per foot, *read* 1°F. per foot.

" 190, Table 1, *insert* Kakabeka conglomerate *below* Gunflint iron formation; *for* Osler slates, *read* Sibley clastics and limestone; *for* Sibley volcanics, *read* Osler volcanics.

" 326, line 5, *for* intermont, *read* interfluve.

" 329, line 24, *for* end, *read* ends.

" 345, line 28, *for* not due to, *read* not as due to.

" 636, Plate 2, *left-hand column should be titled* Average section for western area; *right-hand column,* Average section for eastern area.

" 640, line 6, *should read* Incidentally, the Dakota as determined by Boutwell on the Weber River north of Peoa, is, in the writer's opinion, a conglomeratic member of the Morrison formation.

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GRANITIZATION, ALBITIZATION, AND RELATED PHENOMENA IN THE NORTHERN INYO RANGE OF CALIFORNIA-NEVADA

BY GEORGE HAROLD ANDERSON

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INTRODUCTION

Petrographic examination of a body of intrusive igneous rocks in the White Mountain, or northern Inyo, Range of California and Nevada shows that certain facies have undergone extensive changes in composition and texture since their primary crystallization. These alterations include the albitization of the potash feldspars, the partial sericitization and epidotization of the plagioclase feldspars, and the formation of biotite, chlorite, magnetite, and other secondary minerals, with accompanying textural changes. To describe these modifications and to attempt to account for their origin is the purpose of this paper.

The peculiarities exhibited by these rocks attracted the attention of the writer while he was making a study of the general geology of the northern half of the White Mountain quadrangle. It soon became evident that changes in mineralogical and chemical composition were of such fundamental importance that they merited further study. Accordingly, portions of two summer field seasons and an academic year of laboratory work were devoted to the problem. The principal objects of these investigations have been to determine (1) the degree to which the rocks have been altered, (2) the limits of the area in which the alterations have been effective, (3) the relationship between the albitization of the potash feldspars and other types of changes involved, (4) the processes which controlled the alterations, and (5) the probable origin of the solutions that carried reacting materials into the rocks. If the problem has not been entirely solved, it is hoped that the accumulated evidence may ultimately point the way to a satisfactory solution.

Financial support for the undertaking has been provided by the Geological Society of America, which, in August of 1933, made a grant of $1100 from its Penrose Bequest for the purpose; by the National Research Council, which made available a grant-in-aid of $360; and by the California Institute of Technology, which contributed $300 for field expenses during the summer of 1933.

The laboratory work, which constituted an important part of these studies, was carried on chiefly at the California Institute of Technology, in Pasadena. To the various members of the staff of the Division of Geology and Paleontology, especially to Dr. Ian Campbell, Associate Professor of Petrography, the writer is under deep obligation for much valuable advice and criticism. Several members of the United States Geological Survey, including especially Dr. Waldemar T. Schaller and Dr. Clyde P. Ross, have assisted by suggestion and comment. Thanks are also due to Professor John P. Buwalda and Professor F. L. Ransome, of the California Institute of Technology, to Professor W. J. Miller, of the University of California at Los Angeles, to Dr. James Gilluly and Dr. Thomas B. Nolan, of the United States Geological Survey, and to Professor Frank F. Grout, of the University of Minnesota, for their critical reading of the manuscript.

The writer wishes to acknowledge, also, the assistance of students employed by N. Y. A. funds at the California Institute of Technology. Mr. Eugene Graham, a senior at the Institute, was particularly helpful.

Most of the drawings were prepared by Mr. Charles A. Dawson, a student in the Division of Geology and Paleontology.

The chemical analyses were made in Los Angeles by Mr. Ed Eisenhauer, Jr. In order to secure as much information as possible with the funds available, the determination of rare elements or of units of little significance in this study has been avoided. None of the analyses, therefore, is complete, and, in some instances, only those units that were of particular interest have been determined. The determination of even such a common unit as P_2O_5, for example, has generally been omitted. Inclusion of the rarer or less prominent elements might have yielded information of value and the failure to determine them may have led to slight errors in the percentage of the other units, but, in the attempt to make the most of the money in hand, possibilities of this kind have had to be discounted.

All analyses were made in triplicate, and the results were checked closely with each other. Where discrepancies were found, the analyses were repeated. It should be kept in mind, however, that, so far as the present study is concerned, possible errors of fractions of a percent are usually unimportant.

GENERAL GEOLOGICAL SETTING

LOCATION

The Inyo Range, which is one of the longest as well as one of the loftiest of the basin ranges, lies just east of the southern Sierra Nevada, from which it is separated by the deep trough of Owens Valley. The northernmost part of the range is in the latitude of San Francisco; the

southern termination is in the Coso Mountains, south of Owens Lake and southeast of the highest portion of the Sierra Nevada. The entire range is more than 100 miles long; its highest peak is 14,242 feet above sea level.

FIGURE 1.—*Index map of the area*

The northern part of the Inyo Range—or, more definitely, that part lying north of Westgaard Pass and Deep Spring Valley—is generally known as the "White Mountains." As Knopf and Kirk have pointed out,[1] this is an unfortunate usage, for it has no geographical nor geological basis. The term "Northern Inyo Range" is preferred.

[1] Adolph Knopf and Edwin Kirk: *A geological reconnaissance of the Inyo Range and the eastern slope of the southern Sierra Nevada, California,* U. S. Geol. Surv., Prof. Pap. 110 (1918) p. 17.

STRUCTURE

As Knopf and Kirk have suggested,[2] the Inyo Range is a horst, with down-thrown blocks on the east and on the west.[3]

The date of the faulting and the amount of displacement appear to differ considerably from place to place along the length of the range. The western scarp is higher and steeper than the eastern one; the mountain block has been tilted toward the east. Marginal faults in the northern part of the range are marked by zones of gouge, tens or even hundreds of feet thick where they cross the meta-sediments. Deformation resulting from compression has also been disclosed in the petrographic study of the intrusive rocks. Outside of the fault zones, however, the meta-sediments, in general, have not been greatly crushed or folded. They appear to have been most altered by high-temperature emanations from a magma.

Recent renewal of the orogenic movement has formed scarplets in the valley alluvium bordering the mountain block, both east and west of the range.

PRINCIPAL ROCK UNITS

The oldest rocks within the uplifted block are pre-Cambrian argillites, quartzites, limestones, and schists, unconformably overlain by Cambrian sandstones and limestones. Interbedded with the argillites and quartzites is a thick series of greatly altered volcanic rocks, mostly fine-grained, dark-colored, and, in places, highly silicified or amphibolitized. In some exposures, they are with difficulty distinguished from the argillites.

Both meta-sediments and interbedded volcanics have been intensely metamorphosed by intrusive rocks, ranging in composition from quartz diorite to granite. The more acidic of these intrusives are probably Jurassic, but the quartz diorite may be much older.

The thickness of the series is difficult to estimate; it probably is not less than several thousand feet.

Large areas of Tertiary and Quaternary lavas overlie both granites and sediments or, in places, form small intrusive bodies. Both flow rocks and pyroclastics are found. The middle to late Tertiary lavas range in composition from andesites to rhyolites. The most recent flows are basalt.

Although at Tonopah, less than 50 miles away, the volcanic series of

[2] *Op. cit.*, p. 13.

[3] G. H. Anderson: *Geology of the north half of the White Mountain quadrangle*, Vol. I, *General geology* (Doctor's Dissertation), Calif. Inst. Tech. (1933).

possibly equivalent age includes keratophyres as prominent members,[4] examination of thin sections of the northern Inyo Tertiary and Quaternary lavas gives no indication that any of them are markedly sodic. Zones of hydrothermal alteration of the volcanics extend along the northeastern boundary of the range, where they are parallel to, or coincide

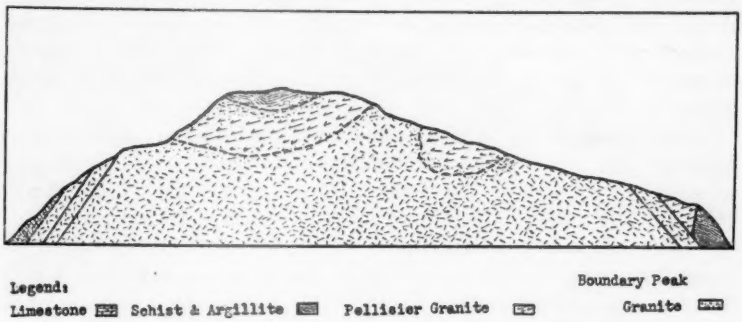

FIGURE 2.—*Generalized section across the northern Inyo Range*

Showing the common relation between granites and meta-sediments, 3 or 4 miles north of White Mountain Peak. The section does not represent any definite locality and is only approximately to scale. The vertical scale is exaggerated.

with, the main marginal fault systems. In these zones, a few small epithermal deposits of gold and quicksilver are found.

Glacial moraines are found in many of the eastward-sloping canyons, the heads of which are fresh Tioga-stage cirques. On the crests of some of the interstream ridges, small remnants of glacial material represent the accumulation of an earlier Pleistocene stage. Nearly all the glacial débris lies above 8000 feet.

Upfaulted alluvium is found at elevations as high as 10,000 feet, most of it overlain by Quaternary basalt.

DETAILED DESCRIPTION OF GRANITES AND META-SEDIMENTS

GENERAL STATEMENT

One of the granites of the northern Inyo Range, the Pellisier granite, may have been formed by some process other than crystallization from a magma.

---

[4] T. B. Nolan: *The underground geology of the western part of the Tonopah mining district, Nevada*, Nev. State Bur. Mines, Bull., vol. 24, no. 4 (1930) p. 13, 14.

Ian Campbell: *The petrography of Tonopah, Nevada* (Doctor's Dissertation), Harvard Univ. (1931) p. 29-89.

Since the publication of the preliminary report on Tonopah, Dr. Nolan has decided that the albite in the volcanics is of secondary origin. (Oral communication.)

COMPARISON OF THE GRANITES

The granites herein described are part of a large subjacent body, for which the term "Inyo Batholith" is proposed. This mass crops out at intervals along nearly the entire length of the Inyo Range. Estimation of its average composition is difficult; local variations range from siliceous granite to gabbro and pyroxenite, but the largest exposures are of biotite granite and hornblende granite, in both of which oligoclase forms a large proportion of the feldspars. The granites are probably approximately equivalent in age to the Sierra Batholith—that is, middle or upper Mesozoic.

If the smaller facies be disregarded, these intrusives are divisible into two units, for which the terms "Boundary Peak Granite" and "Pellisier Granite" are proposed. The former is the rock of which Montgomery Peak and Boundary Peak, the two sharp pinnacles at the extreme northern end of the range, are composed. Visible for many miles in all directions, these peaks served as landmarks for pioneers, and their shining white summits early suggested "White Mountains" as a name for the range. The Pellisier granite (Pl. 3, fig. 4) is typically exposed on a surface of low relief, designated as "Pellisier Flats" on the topographic sheet, which occupies a comparatively large area along the crest of the range.[5]

The two granites differ decidedly from each other in appearance, in structure, and in mineralogical and chemical composition, yet few definite contacts are found between them. Generally, the transitions from the one to the other are gradational. In a few localities, abrupt contacts are found, but most of these appear to be due to faulting.

One of the most strikingly apparent differences between the Boundary Peak and the Pellisier granites is in color. The Boundary Peak granite (Pl. 3, fig. 1) is light gray, almost white in some areas; the Pellisier, on the other hand, varies from medium to dark gray. The difference in shade is due not only to the higher ferromagnesian mineral content of the Pellisier granite but also to a prevailing bluish-gray tint of its quartz and feldspars. This color of the Pellisier so closely resembles that of the argillites and phyllites with which it is in contact that the two cannot be readily distinguished at a distance. The difficulty is augmented by the presence, in the Pellisier granite, of structures strikingly similar to those ordinarily associated with sedimentary rocks (Pl. 2).

The Boundary Peak granite is fairly uniform in appearance and composition throughout the northern Inyo Range. The Pellisier granite, on

[5] This surface is in part an uplifted oldland. *See* G. H. Anderson and J. H. Maxson: *Physiography of the Northern Inyo Range* [Abstract] Geol. Soc. Am., Cordilleran Sect., Pr., 1934 (1935) p. 318; [Abstract] Pan-Am. Geol., vol. 61 (1934) p. 314-315. J. H. Maxson and G. H. Anderson: *Terminology of surface forms of the erosion cycle*, Jour. Geol., vol. 43 (1935) p. 88-96.

PINNACLES IN BOUNDARY PEAK GRANITE

Produced by characteristic jointing. The highest point is Boundary Peak. The pine trees in the lower half give the scale.

FIGURE 1. CONTACT BETWEEN BOUNDARY PEAK GRANITE (RIGHT) AND PELLISIER GRANITE (LEFT)
Just south of Boundary Peak. Showing characteristic pseudo-sedimentary structure of the Pellisier granite (upper left).

FIGURE 2. PSEUDO-SEDIMENTARY STRUCTURE IN GRANITE
North of the mouth of Perry Aikin Canyon. A small exposure of schist (dark) is shown on the hillside just above, and to the left of, the mouth of the large canyon on the right.

the contrary, is decidedly variable in both composition and texture. Marked differences are evident, for example, in the kind, proportion, and arrangement of ferromagnesian minerals. Hornblende, biotite, and iron oxides, with epidote, chlorite, and other dark-colored constituents, compose from 5 to 25 per cent, or more, of the rock in some areas. Although hornblende is commonly present in the Pellisier granite (in contrast with the Boundary Peak, in which it is rarely found) it is almost, if not altogether, absent from some large areas. Other significant differences in mineralogical composition are discussed elsewhere in this paper.

In general, the Pellisier granite is coarser-grained than is the Boundary Peak, though fine-grained facies of both are abundant. The arrangement of the grains is different in the two rocks. In the Boundary Peak granite, for example, the mafic minerals are distributed fairly evenly throughout the mass. In the Pellisier granite, on the contrary, the mafic constituents are unevenly distributed, giving a somewhat mottled appearance. The Pellisier granite, furthermore, tends to be porphyritic; in places, it is markedly so. The Boundary Peak granite, in contrast, is nearly everywhere even-grained, except near the contacts with the argillaceous sediments, where it, also, is commonly porphyritic and in other respects becomes more similar to the Pellisier.

The Boundary Peak granite is closely jointed, with one direction of jointing much more pronounced than the others. In consequence, the rock forms sharp pinnacles (Pl. 1), and most of the spalled-off fragments that accumulate to form talus slopes are relatively thin elongated slabs. The structure gives an impression of having been produced by shearing, but no typical cataclastic textures appear in thin sections. The Pellisier granite is much more massive in general appearance, but thin sections of some exposures show considerable strain or crushing. A possible explanation is that, in the case of the Boundary Peak granite, relief from deforming pressures was afforded by movements along parallel joint planes, whereas, in the less closely jointed Pellisier, an actual crushing took place.

Perhaps the most significant difference between the two granites is in the abundance of inclusions. Xenoliths and other inclusions are rare in the Boundary Peak granite. In the Pellisier granite, they are abundant in a wide range of sizes and all degrees of digestion or replacement. Most of the xenoliths appear to have been schistose or argillaceous in original composition. They are nearly all elongated and are in parallel orientation. In places, this is on such a large scale as to indicate that the sediments, or the metamorphic rocks from which they were derived, were only slightly, or not at all, dislocated when the granite was formed.

In places, the Pellisier granite has an appearance that, viewed from a

distance, strongly resembles stratification in bedded deposits; this is found, even where xenoliths may not be especially abundant (Pl. 2).

A short distance north of Perry Aikin Canyon, for example, the granite has a pseudo-sedimentary structure, which appears, viewed from a distance, to have the same attitude as adjoining sediments. Robert Sharp, a graduate student at Harvard University, has informed the writer that, in Birch Canyon, farther south in the Inyo Range, near the northern boundary of the Bishop quadrangle, he has observed pseudo-sedimentary structures in granite that appear to be continuous with the stratification of adjoining sedimentary rocks.

About a mile north of the first canyon north of Leidy Canyon, the granite possesses gneissic or foliated structure that exactly parallels the schistosity of partly "digested" xenoliths; this schistosity can be traced directly into comparatively little altered schists, about a mile down the canyon. In about the same distance up-canyon, it can be traced gradationally into typical Boundary Peak granite.

Except at the extreme northern end of the range, the principal outcrops of the Pellisier granite lie at higher elevations than those of the Boundary Peak. In general, the Pellisier occupies the crest of the range, from Montgomery Peak south to Indian (McNett) Canyon; the Boundary Peak granite appears to emerge from beneath a relatively thin covering of Pellisier granite and meta-sediments. In most places, this roof is not more than 2000 or 3000 feet thick. This distribution of exposures of the Boundary Peak indicates that it forms a large underlying mass. Its total volume is probably much greater than that of the Pellisier granite. The general relations in space and relative volume between the two bodies of granite are indicated diagrammatically in the accompanying sketch (Fig. 2). Almost all exposures of Pellisier granite are in close proximity to exposures of argillites or schists.

PETROGRAPHIC DETAILS OF THE BOUNDARY PEAK GRANITE

The Boundary Peak granite is a fairly homogeneous rock, with no extraordinary variations in composition and texture, even over wide areas. Nevertheless, it exhibits definite changes in both respects as the contact zones are approached. As reference to analyses (1) and (2) will indicate, the soda/potash ratio increases materially as the roof of the batholith is approached. In thin sections, this is seen to be accompanied by an increase in myrmekites but by no apparent change in the composition of the primary feldspars.

The texture of the Boundary Peak granite is normally granitoid, with anhedral plagioclase, orthoclase, and quartz dominating the pattern of the rock. The primary plagioclase corresponds closely in composition

to that of the Pellisier granite—that is, it is oligoclase of about $Ab_{85}An_{15}$. The potash feldspars include both orthoclase and microcline. These are mostly in large grains of "deuteric aspect",[6] apparently replacing plagioclase and some quartz. Many of them are somewhat perthitic, but the albite of the perthite may not all be of replacement origin.

Also present in abundance in the Boundary Peak granite is an untwinned potash feldspar of low refractive index and positive sign, which has been tentatively identified as "isorthoclase."[7]

Almost all the quartz of the Boundary Peak granite exhibits "strain shadows," and it is, in places, biaxial.[8] It is not granulated or shredded, however, and in thin sections the rock rarely shows any other cataclastic phenomena. About 20 to 25 percent of the rock is quartz.

Most of the biotite is in rather large grains, distributed, without pronounced orientation, irregularly through the rock. It is olive-green or brown and strongly pleochroic, commonly intergrown with chlorite, and, in many parts of the rock, it appears to have been entirely altered to chlorite.

Muscovite, presumably of primary origin, is fairly abundant in nearly all sections of Boundary Peak granite.

Myrmekitic intergrowths of quartz and plagioclase are the only prominent secondary structures or textures in the Boundary Peak granite. These are very numerous, however, infringing upon potash feldspars where grains of these minerals are bordered by plagioclase. Their significance will be discussed in more detail later.

Titanite, magnetite, hematite, and a little zircon are the chief accessory minerals.

Analyses 1 and 2 (Table 1) are representative of the composition of the Boundary Peak granite. The former is of a rock from Middle Canyon, at an elevation of 9150 feet. The latter is from the east face of Montgomery Peak, at 11,200 feet. The latter, therefore, was about 2000 feet nearer the roof of the batholith.

For comparison, the average composition of 184 granites younger than pre-Cambrian is given in an adjoining column and in a fourth column, the average of 12 alkaline granites.[9]

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[6] J. L. Gillson: *Granodiorites in the Pend Oreille district of Northern Idaho*, Jour. Geol., vol. 35 (1927) p. 1-31.

[7] L. Duparc: *Sur une nouvelle variété d'orthose*, C. R., vol. 138 (1904) p. 714.

Tom F. W. Barth: *An occurrence of isorthoclase in Virginia*, Am. Mineral., vol. 18, no. 11 (1933) p. 478-480.

[8] P. J. Holmquist: *Zur morphologie der gesteinsquarze*, II-*Die deformationsstrukturen der gesteinsquarze*, Geol. Foren. Forh., Bd. 48, H.3 (1926) p. 410-428. Strain effects in quartz are thoroughly discussed and illustrated.

Some exposures in the highly altered portions of the Pellisier granite suggest the possibility that phenomena similar to pressure shadows and undulatory extinction may be produced in quartz by solution and re-deposition, possibly under pressure.

[9] R. A. Daly: *Igneous rocks and their origin* (1918) p. 19, 20. 1st edition. New York.

"NORMAL" PELLISIER GRANITE

The Pellisier granite, a highly variable rock, is believed to have been formed by the recrystallization of older rocks, with the addition of more or less material from a subjacent magma. The degree of recrystallization and the intensity of alteration varied in different parts of the rock,

TABLE 1.—*Comparison of analyses of Boundary Peak and other granites*
(Ed Eisenhauer, Jr., Los Angeles, analyst)

Constituents	Boundary Peak granite		Averages of granite analyses (Compiled by R. A. Daly)	
	(1) From Middle Canyon, elevation 9150 ft.	(2) From east face Montgomery Peak, elevation 11,200 ft.	(3) Average of 184 granites younger than pre-Cambrian	(4) Average of 12 alkaline granites
SiO_2	70.95	68.35	70.28	73.94
Al_2O_3	17.44	17.49	15.10	12.44
Fe_2O_3	0.62	1.59	1.63	2.60
FeO	1.55	1.73	1.67	1.29
MgO	0.15	0.87	1.09	0.26
CaO	2.05	2.33	2.22	0.46
Na_2O	2.54	3.92	3.31	4.59
K_2O	3.57	3.35	3.98	4.24
TiO_2	0.08	0.07	0.34	0.11
P_2O_5	*	*	0.27	0.05
MnO	*	*	0.11	0.02
Total	98.95	99.70	100.00	100.00
Total alkalies	6.11	7.27	7.29	8.83
Ratio Na_2O/K_2O	0.71	1.17	0.83	1.08

* Not determined.

depending upon position in relation to the magma, upon structure, upon degree of permeability to magmatic emanations, and upon the initial composition and texture of the sediments. Parts of the rock are virtually indistinguishable from a granite formed by crystallization from a magma. Other parts have been less highly altered, and textural and compositional peculiarities remain, which appear to have been directly inherited from the parent sediments or are indicative of sedimentary origin. Between granites and meta-sediments, and also between the two granites, are

transition zones, which, though in general gradational, are in detail extremely complex. Within the contact zones are many rock types, some of them much like the Pellisier granite in appearance and composition, others more nearly resembling the Boundary Peak granite, and still others of a mixed type not clearly to be assigned to any of the three units.

It is difficult to select a single specimen that is even fairly representative of the Pellisier granite as a whole. On the other hand, the analysis of a composite sample would be misleading and valueless. The method adopted has been to select and describe specimens that most nearly resemble a true granite in composition and texture and are as free as possible from the textural and compositional peculiarities commonly exhibited by the rocks of the transition zones. If the Pellisier granite was formed by the alteration and recrystallization of sediments, then the rocks selected for description represent the most highly altered and recrystallized part of the mass. This may be properly referred to as the "normal" Pellisier granite, if the restricted meaning of the term is understood.

This "normal" Pellisier granite contains quartz, moderately albitized potash feldspar, oligoclase (somewhat epidotized and sericitized), biotite, chlorite, magnetite or hematite, a little rutile enclosed in the chlorite, and a few small grains of a mineral that may be staurolite. The potash feldspars are moderately clouded, and the plagioclase grains are heavily clouded by finely divided material, difficult to identify (p. 65). Potash feldspar exceeds oligoclase about 1¼ to 1; about 25 percent of the rock is quartz.

The texture (neglecting the pseudo-cataclastic texture, which, though common, is presumably of secondary origin) is monzonitic rather than granitoid. The plagioclase feldspar grains are commonly subhedral; some are euhedral. Some are poikilitically enclosed in the potash feldspars, but, more commonly, the latter, with quartz, fill the interspaces in a manner suggestive of the deuteric pattern described by Gillson.[10] Locally, quartz appears to have been replaced by potash feldspar.

The composition of the plagioclase feldspar ranges within rather narrow limits. Some is $Ab_{80}An_{20}$, but most of it is about $Ab_{85}An_{15}$. Some grains are zoned, but most of them are not.

Most of the orthoclase and microcline are perthitic, partly caused by replacement, but, in a few instances, probably caused by exsolution,[11] as indicated by "films" and "strings."

[10] J. L. Gillson: *op. cit.*, p. 1-31.

[11] Olaf Andersen: *Genesis of feldspar from granite pegmatites*, Norsk geol. Tidsskr., Bd. X, H. 1-2 (1928) p. 149-173.

Most of the potash feldspar grains are clouded by a finely disseminated mineral, which is probably kaolinite or sericite. Many grains, however, contain minute particles of hematite or magnetite. The inclusions may be so abundant as to render some grains nearly opaque, but other grains are almost entirely clear. Quartz commonly fills the interspaces, but it also is found in small euhedral crystals, enclosed by the plagioclase. Myrmekite is abundant.

Hornblende and biotite, the principal mafic minerals, are commonly 10 to 15 per cent of the rock but may be higher in some exposures. The hornblende is commonly green, but some is bluish, suggesting sodic constituents. It is found interstitially as elongated grains, associated with biotite or chlorite. Less commonly, it is enclosed in plagioclase or orthoclase. Hornblende is abundant in the Pellisier granite as a whole but may locally be scarce or entirely absent.

Biotite is invariably present in the Pellisier granite, and is usually more abundant than hornblende. Its optical properties range widely; from olive-green to brown, and from high to low birefringence. Much of the biotite is enclosed as small, nearly equidimensional flakes, in the feldspar. Some aggregates have an outline suggesting pseudomorphism after pyroxene.

Biotite is commonly altered, wholly or in part, to chlorite, which is weakly pleochroic. Its interference color may be "ultra blue" or peculiar shades of "wine" or "old rose." Chlorite and relatively unaltered biotite are found independent of each other in the same section.

Magnetite, hematite, and titanite are the most common accessories. All three are found in feldspars or in interstices.

The chemical composition of one of the specimens selected for petrographic description is given in Analysis No. 5. With this is compared the average composition of 184 granites younger than pre-Cambrian, that of 12 alkaline granites, and that of 20 sub-alkaline granites (from Rosenbusch) as presented by Daly.[12]

Compared with the average of 184 granites, this specimen of "normal" Pellisier granite is relatively high in iron and low in total alkalies (Table 2). The rather high ratio of soda to potash is compatible with the belief, confirmed by the study of thin sections, that albite has partly replaced potash feldspar. This specimen is less highly albitized, however, than most of the Pellisier granite. Alumina and lime are also fairly high. In other respects, the composition closely resembles that of an average oligoclase granite.

META-SEDIMENTS

On the flanks of the northern part of the Inyo Range are found dolomitic limestones, argillites, and schists, probably of pre-Cambrian age. On the crest of the range, just north of White Mountain Peak, and

[12] R. A. Daly: *op. cit.*, p. 19-20.

occupying the western slope from White Mountain Peak south to the northern boundary of the Bishop quadrangle, and perhaps beyond, are sandstones, quartzites, limestones, argillites, stream-conglomerates, and

TABLE 2.—*Comparison of analyses of "normal" Pellisier and other granites*
(Ed Eisenhauer, Jr., Los Angeles, analyst)

Constituents	(5) Pellisier granite	Averages compiled by R. A. Daly		
		(3) 184 granites younger than pre-Cambrian	(4) 12 alkaline granites	(6) 20 sub-alkaline granites
SiO_2	69.81	70.28	73.94	69.82
Al_2O_3	16.57	15.10	12.44	14.53
Fe_2O_3	1.45	1.63	2.60	2.00
FeO	3.00	1.67	1.29	1.68
MgO	0.46	1.09	0.26	1.16
CaO	2.80	2.22	0.46	2.21
Na_2O	2.70	3.31	4.59	3.51
K_2O	2.47	3.98	4.24	4.26
TiO_2	0.17	0.34	0.11	0.41
P_2O_5	*	0.27	0.05	0.30
MnO	*	0.11	0.02	0.12
Total	99.43	100.00	100.00	100.00
Total alkalies	5.17	7.29	8.82	7.77
Ratio Na_2O/K_2O	1.09	0.83	1.08	0.82

* Not determined.

meta-volcanics. These may be in part Cambrian, but, for the most part, they are undoubtedly pre-Cambrian.

The dolomitic limestones and marbles are of varying degrees of purity, grading into calcareous shales. The argillaceous rocks are of black carbonaceous shales, quartz-mica schists, and argillites and phyllites in different stages of alteration and recrystallization. The argillites and phyllites are ferruginous, the iron content averaging about 5 per cent.

Conglomerates and quartzites are rare north of Leidy Canyon, but farther south they become increasingly abundant. In the vicinity of White Mountain Peak, beds of quartzite, hundreds of feet thick, are interbedded with meta-volcanics.

The older rocks bear little resemblance to the Cambrian rocks in the vicinity of Westgaard Pass, mapped and discussed by Knopf and Kirk.[13] On the other hand, some of them closely resemble the "dolomitic limestones and marble, quartzites and green knotted schists," which, in the Silver Peak quadrangle, less than 50 miles to the east, underlie, with apparent conformity, the lowest fossiliferous Cambrian.[14] Turner suggests that these beds may represent the base of the Cambrian or that they may be pre-Cambrian in age.[15] Kirk believes that the basal dolomite of Spurr and Turner is a correlative of the pre-Cambrian Reed dolomite of the northern Bishop quadrangle, but he is in doubt about the overlying quartzites and schists.[16]

The chemical composition of typical specimens of phyllite and schist is given in analyses. No. 7 (Table 8) is a phyllite from the crest of the range, about 4 miles northwest of White Mountain Peak. No. 8 (Table 3) is a schist from the east front of the range, about half a mile from Boundary Peak granite. No. 9 (Table 8) is that of a composite of several specimens of schists from the south branch of Indian (McNett) Canyon, about half a mile from an exposure of Boundary Peak granite. The appearance of the latter gives the impression that it has been somewhat altered by magmatic emanations.

CONTACT ZONES

SUMMARY OF VIEWS CONCERNING CONTACT PHENOMENA

Definition.—It may be helpful at the beginning of the discussion to summarize briefly the views of the writer, concerning the contact phenomena. These are based upon observations in the northern Inyo Range and in other localities where similar conditions exist.

The effects of igneous intrusion upon a country rock are commonly called "contact metamorphism," but this term is used somewhat differently by different writers. Barrell,[17] for example, distinguishes between contact metamorphism and contact metasomatism, as separate processes in the alteration of the invaded rocks. Under contact metasomatism, he includes pneumatolytic and hydrothermal metasomatism. Contact metasomatism, he believes, depends upon a "temporary permeability" of the affected rocks, produced by minute fracturing or parting, "the evidence

[13] Adolph Knopf and Edwin Kirk: *A geological reconnaissance of the Inyo Range and the eastern slope of the Southern Sierra Nevada, California*, U. S. Geol. Surv., Prof. Pap. 110 (1918) p. 25-130.

[14] J. E. Spurr: *Geology and ore deposits of the Silver Peak quadrangle, Nevada*, U. S. Geol. Surv., Prof. Pap. 55 (1906) p. 18.

[15] H. W. Turner: *Contribution to the geology of the Silver Peak quadrangle, Nevada*, Geol. Soc. Am., Bull., vol. 20 (1909) p. 238.

[16] Adolph Knopf and Edwin Kirk: *op. cit.*, p. 23.

[17] Joseph Barrell: *Geology of the Marysville mining district, Montana*, U. S. Geol. Surv., Prof. Pap. 97 (1907) p. 116-118.

of which has been in many places nearly destroyed by the metasomatic recrystallization."

In his study of the Kristiania region, V. M. Goldschmidt [18] recognized an older "normal" contact metamorphism without addition of material, and a younger "pneumatolytic" metamorphism by recrystallization, with addition of material through gases from the magma.

Similarly, Umpleby [19] describes two stages of metamorphism at White Knob, Idaho: (1) Contact metamorphism during the intrusion, (2) Contact metasomatism after consolidation of the magma.

Lindgren [20] uses the terms (1) "Igneous (pyro) metamorphism," which he defines as a high temperature process, about equivalent to contact metamorphism, but including also the effects of igneous injection and pegmatitization, and (2) "hydrothermal metamorphism," which includes the changes effected in rocks by hot ascending waters. The first may be local or regional and in part involves changes of composition; the second is local and in almost every instance involves changes in composition.

Probably, however, the effects of contact metamorphism and contact metasomatism, although theoretically distinct, can rarely be entirely separated. To a considerable extent the one depends upon the other, and their effects coincide or overlap. Even in a metamorphic rock in which there has been no change in the chemical composition of the mass, the secondary minerals, as Lindgren [21] points out, result from metasomatic action. The rocks themselves, however, are termed metasomatic only "if their composition has been materially changed by replacement of the original minerals."

It should be unnecessary, of course, to direct attention to the fact that metasomatism (replacement) nearly universally takes place without change of volume, especially if pressures are high.

The writer is entirely in agreement with Lindgren's [22] view that "if we conceive magma rising to regions of lessening pressure, . . . it is difficult to see why the escape of gases should not have begun *at once* when the melt was brought into contact with the cooler surrounding sediments. . . .

"The volatile substances were concentrated in the upper parts, or cupolas, of the intrusives. . . .

". . . contact phenomena may vary greatly in different places. At times contact metamorphism is very weak while the metasomatic phases

[18] V. M. Goldschmidt: *Die kontaktmetamorphose im Kristianiagebiet* (1911) Kristiania.

[19] J. B. Umpleby: *Geology and ore deposits of the Mackay region, Idaho*, U. S. Geol. Surv., Prof. Pap. 97 (1917) 129 pages.

[20] Waldemar Lindgren: *Mineral deposits* (1933) p. 91. New York.

[21] *Op. cit.*, p. 91.

[22] *Op. cit.*, p. 703.

are strong, and *vice versa*. Undoubtedly emanations along fissures continued after the general consolidation in many places. . . ."

If a magma intrudes sedimentary or metamorphic rocks, it will produce effects that will vary from place to place, depending upon several conditions, most important of which are: (1) Character and composition of the magma, (2) character and composition of the invaded rocks, (3) structure of the invaded rocks, (4) position of the invaded (country) rocks, and (5) the depth at which the magma consolidated.

Character and composition of the magma.—Granite magmas commonly give rise to more profound changes in the intruded rock than do less silicic ones, which may be due, in part, to their generally higher content of volatile substances and to the relatively greater proportion of end-stage concentrations. It may also be due partly to the considerable differences in chemical composition that exist between granite magmas and many sediments.

The heat content of the magma is important. This is related both to the temperature and to the size of the magma. Ordinarily, magmas with higher thermal content will produce more profound changes than do those with lower thermal content.

In this discussion, no account is taken of the different theories of how magmas may have been formed or have come into position. Some students doubt the existence of granite magmas; others, that alkaline rocks were formed by simple crystallization from magmas of corresponding composition. The writer believes that granite magmas do exist, however, and that they may actually be intruded into older rocks.

Concentration of albite takes place as a result of conditions that prevent a continuous series of reactions during the crystallization of the plagioclase feldspars, with constantly falling temperatures.[23] Similarly, interruptions in the crystallization of minerals belonging to the discontinuous reaction series (i.e., those exhibiting incongruent melting) may, under like conditions, be responsible for minerals that would not have formed in the normal course of crystallization, and for the concentration of certain elements—for example, silica—in the end-stage liquids. An excess of water (liquid or vapor) or of other "mineralizers" may serve to keep these substances fluid. They may become concentrated in the interstitial liquids of the outer parts of the intrusive while crystallization is still incomplete (i.e., while the body is still in the "mushy condition") or, probably more commonly, as solidification proceeds from the margins inward, and downward, the concentration takes place at greater depths. In late stages of magmatic development, pressures become so great that

[23] James Gilluly: *Replacement origin of albite granite near Sparta, Oregon*, U. S. Geol. Surv., Prof. Pap. 175 C (1933) p. 77.

these end-stage fluids are forced into the outer parts of the intrusive or into the country rock, where, being out of equilibrium with minerals already formed, they react with, or replace, the latter.

These are the so-called "deuteric" reactions. Hitherto, these have been considered to affect only the outer portions of the intrusive mass itself, but there appears to be no good reason why similar reactions may not also be effective in producing replacements and alterations in the nearby country rock.

The equilibrium existing between minerals and the liquid with which they may be in contact is conditioned by temperature, pressure, composition, and concentration. Changes in any of these may cause the existing minerals to be resorbed and new ones to be deposited in their place. This is the fundamental factor in replacement. The general rule, applicable both in recrystallization and in replacement, is that the mineral or the mineral assemblage tends to be formed that is most stable under the existing physical and chemical conditions.

In an assemblage of minerals of different compositions, an individual mineral may not react as it would if it were alone or were surrounded by others of its own kind. A widely known example of this is the localization of myrmekite where plagioclase joins potash feldspar. If myrmekite is formed by replacement, as many believe, the process ordinarily goes on only where the two types of feldspar are in contact.

Gaseous and liquid effusions of various kinds are given off at various stages in the emplacement of a batholith. Many investigators believe that emanations are discharged before crystallization is well under way.

> "The escape of these substances, as pointed out by Harker, may not have been uniform. A large part was doubtless given off while the magma was still fluid. Another part may have been liberated at the time of consolidation; still another part may have been retained until cooling had advanced considerably. Finally, fissures and shattering of the partly consolidated or congealed mass may have permitted gases from the still fluid interior or basal part to reach the outside of the intrusions."[24]

Doubtless, the most active period is during the later stages of crystallization, when pressures are highest and the concentration of magmatic fluids is greatest.[25] Just before final consolidation, the end-stage emanations especially rich in albite and silica become of maximum influence (Fig. 3).

Many assume that a magma comes into place in one continuous movement "from depth," but available evidence appears to sustain the theory

[24] Waldemar Lindgren: *op. cit.*, p. 699.

[25] W. H. Emmons: *On the mechanism of the deposition of certain metalliferous lode systems associated with granitic batholiths: Ore deposits of the Western States* (Lindgren volume), Am. Inst. Min. Metall. Eng. (1933) p. 336, fig. 5.

that the advance of magma takes place in a series of movements, separated by pauses (some, perhaps, prolonged) during which partial solidification occurs, especially in the marginal portions. This causes an overlapping or telescoping of effects in the country rocks, earlier alterations being intensified or partly obscured by later ones. At least one eminent American petrologist concurs in this opinion.[26]

Most sedimentary and meta-sedimentary rocks contain more or less water, either mechanically included or in chemical combination, as water of crystallization. The heat from an intrusive may, and undoubtedly commonly does, set these waters into active circulation, providing a means by which transfer and exchange of materials can take place.

The objection may be raised that active circulation of fluids is not possible in such dense rocks as granites, argillites, or quartzites. The evidence of disseminated ore deposits, however, contradicts this view.[27] H. J. Fraser and the writer have obtained experimental evidence that aqueous solutions under small pressures and room temperatures can penetrate massive unfractured rocks, such as granite, for distances of several inches in all directions within 24 to 48 hours. The details of these experiments will be published later.

Character and composition of the meta-sediments.—Different types of sedimentary rocks are affected very differently by intrusions, the differences depending upon both texture and composition. Dense massive rocks, such as impure quartzites, are less permeable to magmatic emanations than are more porous ones, but they may be better conductors of heat and may be more thoroughly recrystallized without addition of material. Rocks, such as schists, which offer more ready access for fluids entering from the magma, on the other hand, may undergo more thorough replacement recrystallization.

If these rocks are composed chiefly of minerals that are relatively stable under the conditions of heat and pressure existing during the period of intrusions, they are less likely to be altered than those consisting of less stable minerals. Some minerals have a wide range of stability, whereas for others the stability range is limited.

The extremely important "reaction principle" of Bowen may have a profound influence, also. If magmatic material comes in contact with sedimentary rocks under conditions of temperature and pressure that remain fairly constant for a considerable period, the changes that take place will depend largely upon the mineralogical composition of the

[26] Charles P. Berkey: *Oral communication*, January 1936.

[27] J. L. Gillson: *The granite of Conway, New Hampshire, and its druse minerals*, Am. Mineral., vol. 12 (1927) p. 319.

J. F. Kemp: *The pegmatites*, Econ. Geol., vol. 19 (1924) p. 711-712.

FIGURE 1. BOUNDARY PEAK GRANITE
Showing typical texture. About ¾ natural size.

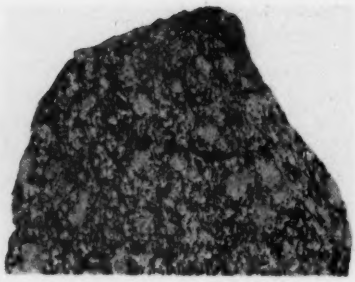

FIGURE 2. GRANITE IN INTERMEDIATE STAGE OF FORMATION BY RECRYSTALLIZATION OF SCHIST
Potash feldspar metacrysts enclosed in a groundmass that preserves many of the structural and compositional features of the schist. Rock grades laterally into one indistinguishable from a true granite. About ⅔ natural size.

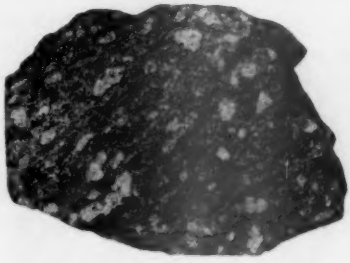

FIGURE 3. ARGILLITE IN EARLY STAGES OF RECRYSTALLIZATION THROUGH CONTACT METAMORPHISM
Metacrysts are partly albitized potash feldspars. Specimen was taken from a point about half a mile horizontally from true granite. About ½ natural size. Chemical composition given in Analysis No. 13.

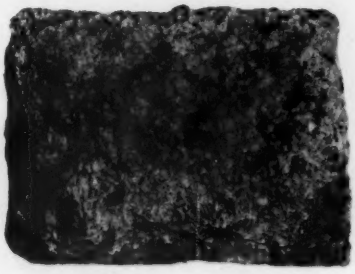

FIGURE 4. TYPICAL PELLISIER GRANITE
From crest of northern Inyo Range. About ¾ natural size.

GRANITES AND GRANITIZED ARGILLITE AND SCHIST

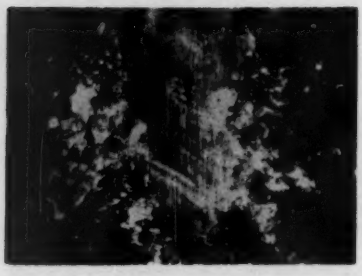

FIGURE 1. MARGINAL CORROSION STRUCTURE
Microcline grain (center) is being attacked from the margins by the groundmass, which contains myrmekites and albite. One of the grains on the border of the microcline (upper right) shows albite twinning. Crossed nicols, x 27.

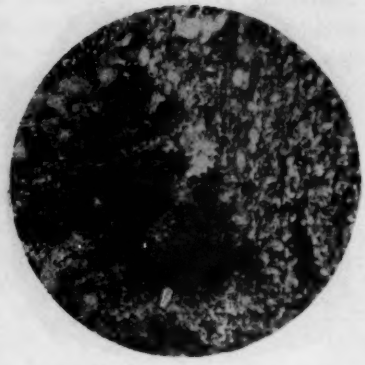

FIGURE 2. "GHOST CRYSTAL" OF MICROCLINE
In extinction position. Forming by replacement and absorption of schist groundmass. Photomicrograph, crossed nicols, x 27.

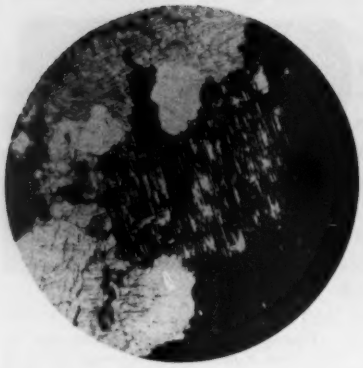

FIGURE 3. CHESS-BOARD ALBITE IN HIGHLY ALBITIZED PELLISIER GRANITE
Photomicrograph, crossed nicols, x 27.

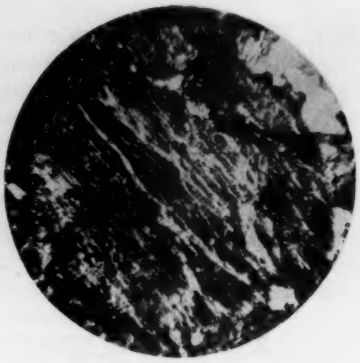

FIGURE 4. STREAKY PERTHITE
With braided veinlets of albite in orthoclase from Pellisier granite. Photomicrograph, crossed nicols, x 27.

MICROSTRUCTURES ASSOCIATED WITH REPLACEMENT

invaded rock, not all the minerals of which will be affected equally or in the same way. If the writer correctly understands the reaction principle, some minerals would be dissolved and actually made a part of the solutions; others would be reacted with, and changed over into, new minerals in equilibrium with the magmatic fluids under the given conditions, without being converted to the liquid state. Thus, in a meta-sedimentary rock containing quartz, plagioclase and potash feldspar, and biotite, invaded by emanations from a magma in advanced stages of crystallization, the plagioclase might be partly or completely made over into a less calcic form; the biotite might be changed to chlorite; and the quartz and potash feldspar might be relatively little changed except in quantity. Under somewhat different conditions, the potash feldspar might also undergo alteration to albite, and, with solutions still richer in soda and perhaps also at lower temperatures, both plagioclase and potash feldspars might be changed to albite. Under different temperature and pressure conditions, however, the reactions might not occur at all, and the net change in the invaded rock might be slight. In such instances, the actual contact between intrusive and country rock would probably be a sharp one, in contrast to the gradational one resulting from the first set of conditions.

Thus, all types of alterations are possible, ranging from simple recrystallization to a complete making-over of the country rock.

The initial character of the invaded rock may be, to a considerable degree, preserved in the product. Textural variations will depend both upon the texture of the country rock and upon the kind and degree of alteration. In incomplete stages, structures, such as schistosity, bedding, and jointing of the country rock, may be almost entirely preserved. In nearly complete stages of recrystallization and replacement, these structures may be almost entirely destroyed, but vestigial remnants usually can be seen, especially from a distance. In the northern Inyo Range, relict structures of this kind in several places can be traced into adjacent meta-sedimentary rocks.

Structure of the country rock.—The alteration of rocks by processes of contact metamorphism is controlled to a marked degree by structural conditions. Emanations derived from a magma take advantage of various kinds of channel-ways, which offer relatively little resistance to their progress. These channel-ways include fractures of various kinds: joints, planes of schistosity in foliated rocks, bedding planes, and, more minutely, cleavages and crystal boundaries. As is well known, rocks with bedding planes that dip into an intrusive at a high angle are altered for a much greater distance than are those in which the bedding planes are horizontal

or dip away from the intrusive. This fact testifies to the importance of magmatic solutions in contact metamorphism.

On the other hand, relatively little altered sedimentary rocks may be faulted into proximity to the intrusive after the latter has given off most of its volatile material. An example is found in the Queen Canyon region in the northern Inyo Range, where comparatively little altered schists are found in immediate contact with the intrusive.

Position of the country rock.—In the northern Inyo Range, a marked difference in the kind of alteration is observed between those rocks that overlie the Boundary Peak granite and those that are upon its flanks. In general, the overlying sediments are more highly altered than those on the margins. This is to be expected, for it is from the upper parts of a batholith, especially the cupolas, that emanations stream most rapidly and in greatest quantity.

The difference, however, is not only in intensity but also in kind of alteration. In most places, the overlying rocks have been greatly enriched in soda. Some of the roof rocks now consist almost entirely of albite and quartz. In contrast, the marginal wall rocks have been enriched in potash, most commonly with the formation of porphyroblasts of potash feldspar. Enrichment in silica appears to have been brought about in both positions.

These differences in intensity and in type of alteration may not be due altogether to difference in position but also to the kind of country rock involved. Most of the rocks overlying the Boundary Peak granite are phyllites and argillites; those on the flanks are chiefly schists and limestones.

Depth of burial may have been important in the kind and intensity of alteration. At great depths, the blanketing effect of the overlying rocks would bring about a more gradual loss of heat from the magma and thus permit higher temperatures in the country rock for greater distances from the intrusive. Because the changes depend upon temperature and pressure as well as upon the composition of the magmatic emanations, this consideration is important.

Replacement and recrystallization versus "injection".—Hitherto, most migmatites have been considered to have been formed by the actual injection of magmatic material in thin sheets between beds, or lamellae, of sedimentary or schistose material. It is difficult for the writer to visualize how this process could be carried on, especially where thin sheets can be traced hundreds, or even thousands,[28] of feet from the actual "contact." It seems more reasonable to believe that these sheets

[28] J. F. Kemp: *op. cit.*, note 25.

of feldspathic and silicic material, say in schists or argillite, to a large extent represent limited migration and recrystallization of materials derived from the schists or argillites, or that they are the result of replacement, the activating agent in both cases being heat from the magma and the transporting agent being fluids penetrating along the bedding planes or planes of schistosity. From re-solution and recrystallization of materials already present in the country rock to the introduction of magmatic material in thin, aqueous solutions from the magma, reacting with or replacing minerals already present, is a process not difficult to visualize. In fact, replacement and recrystallization may not be very different processes. Each may, and in most cases probably does, to some extent involve the other.

The injection hypothesis, as the writer understands it, involves the addition of magmatic material to the country rock, with no corresponding loss. This means either a great increase in density or a great increase in volume of the country rock. But in most instances of this sort, neither density nor volume appears to have been greatly increased. Solution and absorption of material by the magma, followed by crystallization, even though conceivable, appears to be an unnecessarily complicated explanation. To the writer, simultaneous solution and reprecipitation, particle by particle, with or without addition and subtraction of material (i.e., metasomatism, recrystallization), appears to offer a much more satisfactory explanation of the phenomena. The belief is strengthened by observations of "corrosive" and "replacement" textures and microstructures.

CONTACT PHENOMENA IN THE NORTHERN INYO RANGE

General description.—The Boundary Peak and the Pellisier granites are separated from each other, and from the meta-sediments, by complex contact zones, which differ from place to place, depending largely upon variations in the composition, structure, and relative position of the rocks. These zones are classified and discussed in the following groups—

(1) Boundary Peak granite—limestone contact zone.
(2) Pellisier granite—limestone contact zone.
(3) Pellisier granite—argillite and schist contact zone.
(4) Boundary Peak granite—argillite and schist contact zone.
(5) Pellisier granite—Boundary Peak granite contact zone.

This grouping is somewhat arbitrary, inasmuch as the different zones are not everywhere sharply distinct from each other. For example, calcareous shales in places are interbedded with, or take the place of, argillites and schists. With increase in the proportion of calcareous matter, the calcareous shales grade into impure limestones. Similarly, the Pellisier granite typically contains so much sedimentary and meta-

morphic material, in the form of large or small xenoliths, that the Pellisier granite-Boundary Peak granite contact zone is not everywhere clearly distinguishable from the Boundary Peak granite-argillite and schist contact zone. The significance of this condition is enhanced by the Boundary Peak granite-argillite and schist contact zone, which closely resembles the Pellisier granite in appearance and composition.

Boundary Peak granite-limestone contact.—Where the Boundary Peak granite has intruded comparatively pure limestones, the contact zones are rather narrow and, on the side of the granite, fairly sharp and well defined. The limestones are commonly intensely silicified for a few hundreds or, rarely, thousands of feet from the contact. In some instances, only certain beds have been affected; in others, the replacing solutions appear to have permeated the entire mass. The minerals are those ordinarily associated with the contact metamorphism of limestone: chiefly grossularite, almandite, epidote, vesuvianite, wollastonite, tremolite or fibrous amphiboles, and quartz. Deposits of metallic minerals, most of them sulphides of lead and zinc, are found in a few places along the limestone contacts; tungsten in the form of scheelite is also found. Most of these deposits are too small to be of commercial value.

The granite becomes darker in color and duller in appearance as the limestone is approached. This is due largely to an increase in mafic minerals and a decrease in quartz. Hornblende, elsewhere almost entirely absent from the Boundary Peak granite, commonly is found in the endomorphic zone. Plagioclase increases and may become the dominant feldspar. In short, the rock becomes more basic than a true granite. Epidote is abundant for hundreds of feet from the contact, but no limestone xenoliths have been found.

Pellisier granite-limestone contact.—The contact relations between the Pellisier granite and the limestones are as yet unknown. The two rocks have not been observed in juxtaposition except where the one has been faulted against the other. The endomorphosed Boundary Peak granite resembles the Pellisier granite but may be distinguished from it by differences in texture and in composition.

Pellisier granite-argillite and schist contact.—The Pellisier granite is generally separated from schists and argillites by a broad transition zone, in which gradational changes in texture and composition may be observed from one type of rock to the other. The transition is not a simple one, at least not as observed in surface exposures. Structural conditions and initial lithological differences introduce so many complications that the detailed study of the zone leads to puzzling and apparently contradictory results. Nevertheless, on the one hand, so little evidence is

found of an intrusive relationship between the Pellisier granite and the meta-sediments and associated rocks, and, on the other hand, progressive stages in alteration and recrystallization of sediments to granite, are so well illustrated by the rocks of intermediate position that the writer has little doubt that the zone is, indeed, a transition, rather than a contact, zone and that the Pellisier granite is not a true intrusive.

Boundary Peak granite-argillite and schist contact.—Where the Boundary Peak granite is in contact with the schists, quartzites, argillites, and meta-volcanics, it is bordered by an extremely complex inner zone of mixed rocks, beyond which lies an outer zone of partly altered and recrystallized meta-sediments. The two zones together may be from a thousand feet to a mile, or more, in width. In the outer zone, the degree of recrystallization varies from slight to nearly complete, the end-stage product being a rock with granitoid texture closely resembling the Pellisier granite. The mixed rocks, or migmatites, lie closer to the granite and appear to have been formed by the penetration of magmatic fluids into the already partly recrystallized meta-sediments. They are so varied in texture and composition as almost to defy any attempt at a generalized description. Some resemble the so-called "injection-gneisses"; the granitic material, however, is rarely in parallel, or even sub-parallel, bands but is in highly irregular and extremely contorted ribbons and stringers, bulged out here, constricted there, dividing, joining, criss-crossing each other in most intricate and complicated patterns. The groundmass between the bands and the stringers of igneous material is nearly everywhere more or less completely recrystallized to a granite-like rock, which exhibits marked differences in texture and in mineralogical composition within even a square foot, or two, of exposure. Commonly, several stages of alteration and "injection" can be seen. In one of these, the schist or argillite was enriched in magmatic material, which penetrated parallel to the schistosity or bedding; later pegmatitic bands, similar to those just described, from a fraction of an inch to several inches wide, obliquely transected the thin, closely spaced sheets of magmatic material, in some places offsetting them but more commonly not. In other rocks less commonly found, the magmatic material is in thin sheets parallel to the bedding planes.

These thin "sheets" of granitic material along the bedding planes of the sediments are apparent at distances of hundreds, or even thousands, of feet from the intruding granite. It is amazing that magmatic materials giving rise to such thin forms could have penetrated so far from the "contacts." It is questionable, indeed, whether any of the sedimentary rocks exposed in the mountain block are entirely free from magmatic contamination.

The groundmass of argillite or schist is generally comparatively little altered; the granitic material is in nearly straight, regular bands of pegmatitic texture, which may be parallel but more commonly are oblique to the foliation or bedding.

In mixed rocks of another type the magmatic fluids appear to have penetrated along small and closely spaced channel-ways, such as folia-

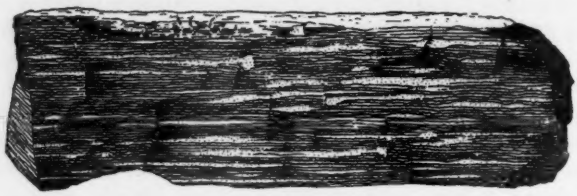

FIGURE 3.—*Argillite containing inter-laminated granitic material*

From Indian Canyon, approximately a third of a mile on the surface from the granite. Drawing from natural specimen, about ⅔ natural size.

tion planes, small fractures, and cleavages, dividing and subdividing until they became more or less completely disseminated through the rock. The effect is as though the meta-sediments soaked up solutions much as a sponge soaks up water. The change in appearance of the rock may be in part due to recrystallization of materials already present and not entirely to replacement. The corrosive textures observed in thin section, however, and the differences in composition, observed in comparing chemical analyses of these rocks with those of the probably corresponding meta-sediments, indicate that metasomatism has played at least some part in the alteration—i.e., the magmatic "juices" appear to have reacted with the sedimentary material until the entire mass was made over into a rock almost indistinguishable from granite.[29]

Usually, this process leads to the formation of feldspar and quartz metacrysts, which may grow in part by displacement but certainly, in many instances, by replacement of the schist or argillite groundmass. Rocks representing intermediate stages of development of this process consist of intricately intermixed magmatic and meta-sedimentary material. In the more advanced stages, the rock closely resembles a granite

[29] J. J. Sederholm: *On migmatites and associated pre-Cambrian rocks of southwest Finland*, pt. 2, Comm. géol. Finlande, Bull. 77 (1926) p. 50. "Thus," says Sederholm, "the idea which these phenomena convey to the observer is that the penetration of the younger granite into the older rocks occurred while these in a large measure retained their former position and that thereby a part of the older rock masses were never entirely solved. . . . The juices of the younger granite permeated the older one as oil penetrates sheets of paper—'a tache d'huile', according to the excellent expression of Termier [Pierre Termier: *Sur la genèse des terrains cristallophylliens*, Intern. Geol. Congr., Stockholm, C. R. (1910) p. 589] and changes them 'ultra-metasomatically' into a new granite which in the final stages was able to react on the older rocks like an eruptive."

in texture and composition. In some exposures, it is indistinguishable from Pellisier granite.

The metacrysts may be closely spaced and limited in size by the comparatively short distances between them (Pl. 3, figs. 2 and 3). The end-product is commonly a rock with an even-grained granitoid texture. It may or may not be gneissic; both are found.

In other instances, the metacrysts are widely spaced, are an inch or more in diameter (Pl. 5, fig. 1; Pl. 6, fig. 2), and form porphyroblasts. If the process continues, the groundmass also is recrystallized or replaced. The resulting rock is a porphyritic granite with phenocrysts (porphyroblasts) of potash feldspar in a more or less thoroughly recrystallized groundmass of quartz, feldspar, biotite, and iron oxides. In many exposures, especially above the Boundary Peak granite proper, the potash feldspars of both groundmass and phenocrysts have been partly or, more rarely, completely altered to albite.

Most of the porphyroblasts are unevenly distributed, many of them in clusters or swarms. Commonly, they include biotite and other minerals inherited from the parent schist or argillite (Pl. 6, fig. 2). The arrangement of these included minerals may be helezitic or concentric. The groundmass may be gneissic, but, more commonly, it is granoblastic. Where it is gneissic, the porphyroblasts ordinarily transect the foliation, but, in a few instances, they displace it.

Evidence that magmatic emanations have played at least some part in the formation of rocks of this type is found in the enrichment in soda (analyses, Table 7). In the unaltered meta-sediments, potash generally exceeds soda. This is the normal relation for sedimentary rocks of this type.[30] These contact rocks, however, commonly have more soda than potash, particularly those found above, rather than on, the flanks of the Boundary Peak intrusive. Examination of thin sections shows that the enrichment in soda is chiefly the result of replacement of potash feldspar by albite. The distribution of the albite-rich zones parallels more or less closely the Boundary Peak granite. It is not unreasonable, therefore, to conclude that the sodic solutions were derived from a magmatic source.

Examination of rocks of this type nearly always discloses relicts of the parent meta-sediment. These relicts may be large, relatively unaltered xenoliths, small shreds of incompletely digested schist, or microscopic fragments or textures obviously inherited from pre-existing rocks. Their peculiarities of texture and composition and the fact that they

[30] E. S. Bastin: *Chemical composition as a criterion in identifying metamorphosed sediments*, Jour. Geol., vol. 17 (1909) p. 466.
Arthur Holmes: *Petrographic methods and calculations* (1921) p. 436. London.

may be traced, with gradual decrease or increase in the proportion of magmatic material, to the country rock on one side and to the true granite on the other furnish convincing evidence that they were not formed by crystallization from a magma, in the commonly accepted meaning of the term. Most of the relict fragments of schist preserve more or less unchanged the initial structural orientation of the metasediments. Magmatic material appears to have penetrated but not to have displaced the country rock.

The effective process may have been a simple recrystallization of the country rock, brought about by heat, pressure, and circulating solutions from the magma, with little or no gain or loss of material. It appears more likely, however, that reaction and replacement played an important part in the transformation. Comparative analyses of sediments, granites, and intermediate rocks indicate, though they do not conclusively prove, that considerable change in chemical composition must have occurred in some, if not in all, cases.

Various terms have been applied to this kind of process. "Granitization" is most common, but it has been loosely used. One eminent petrologist[31] prefers "assimilation," but, to the writer, this term implies that the sediments were absorbed by, and actually made a part of, the magma before crystallization occurred. The abundance of relicts of sedimentary material in parallel structural orientation within these mixed rocks and the gradual decrease in proportion of magmatic material and in intensity of alteration away from the contact indicate that the transformation to granite proceeded without any large part of the zone of the mixed rocks becoming fluid at any one time. In brief, the field relations show that solution and recrystallization went on gradually and almost concurrently, by reaction with, and replacement of, the materials of the solid country rock rather than by the melting and absorption of the country rock, followed by precipitation.

It is possible that a better term may be suggested, but until that is done the writer prefers to use granitization as being the most applicable one available.

None of the sedimentary rocks exposed in the northern Inyo block is altogether free from the effects of contact metamorphism. The "green knotted schists,"[32] which are fairly abundant in the area, especially to the northeast of Queen Canyon and along the western margin of the range, represent the beginnings of recrystallization under contact metamorphism, although they may not have been acted upon to any con-

[31] F. F. Grout: *personal communication.*

[32] A term applied by Turner to similar rocks in the Silver Peak quadrangle [H. W. Turner: *Contribution to the geology of the Silver Peak quadrangle, Nevada,* Geol. Soc. Am., Bull., vol. 20 (1909) p. 239].

siderable degree by igneous emanations. These rocks include andalusite and sillimanite schists of the textural varieties commonly known as "knotenschiefer," "fruchtschiefer," and "fleckschiefer." Ordinarily, such rocks are found only at distances of several thousand feet to a mile, or more, from Boundary Peak granite. In the Queen Canyon region, their position in immediate contact with the Boundary Peak granite is probably due to faulting.

Although it is probable that these rocks have been altered chiefly by thermal metamorphism, it is somewhat questionable whether recrystallization in metamorphic rocks ever begins or proceeds in the complete absence of fluids.[33]

Boundary Peak granite-Pellisier granite contact zone.—In the main, the Boundary Peak granite-Pellisier granite contact zone does not differ greatly from that between the Boundary Peak granite and the argillites and schists. In places, it is gradational—i.e., a gradual transition exists from one rock to the other. Elsewhere, a complex zone of migmatites, pegmatites, and aplites is found between the two granites. This is explainable on the basis of the large amount of sedimentary material included in the Pellisier granite—the migmatite zones are found where the proportion of sedimentary material is exceptionally large. In other words, the Pellisier granite is in, and is a part of, the Boundary Peak granite contact aureole.

In a few localities, a comparatively sharp contact exists between the two granites. In some instances, the sharpness of the contact is undoubtedly due to faulting, but, for others, another explanation must be sought. The writer believes it is to be found in the fact that the Boundary Peak magma was not intruded in a single movement but in repeated movements, separated by more or less prolonged pauses. Thus, sharp contacts can be established with rocks that have been partly or completely recrystallized or replaced during earlier stages of magmatic intrusion. This question will be considered in the discussion of the general problem of the origin of the Pellisier granite.

IRON ENRICHMENT

The normal iron content of the meta-sediments, where they are uncontaminated by igneous material, appears to range from about 5.5 or 6.0 per cent, for the argillites and phyllite, to 7.5 or 8.0 per cent, for the schists. Determinations for the limestones have not been made. The Boundary Peak granite has only about 3 per cent total iron and the Pellisier granite approximately 4 or 4.5 per cent.

Within the contact zone, however, at different distances (usually about a quarter of a mile from the Boundary Peak granite) is an iron-

[33] J. J. Sederholm: *op. cit.*, p. 128.

rich zone, ranging from a few hundred feet to a thousand feet, or more, in width, in which the ferruginous content is 18 to 22 per cent, or even higher. The iron is partly magnetite but is chiefly hematite. It is disseminated both in small particles through the rock and in well-defined veins and seams, consisting almost altogether of hematite. In places, it is the cementing material of fault breccia, for example, in the pass between Indian (McNett) Canyon and Davis Canyon.

This concentration of iron is, in general, more pronounced in the partly altered rocks flanking the batholith than in the roof, but, in a few instances, the reverse is true.

Along some of the fractures and joints of the Pellisier granite, thin veins and seams of hematite are found. Much finely divided hematite is also disseminated through the feldspar and quartz, making them peculiarly bluish-gray. Iron oxides are distributed through the groundmass as well. In the most highly albitized portions of the Pellisier granite, little iron is present, or may be almost entirely absent. In the Boundary Peak granite, the proportion of iron oxides is low. Between the zone of maximum iron concentration and the granite is an iron-poor zone. The following percentages are quoted to show the iron content of different kinds of rocks in various localities. In the Boundary Peak granite, it is 2.1 per cent (Analysis No. 1) to 3.32 per cent (Analysis No. 2). In a typical Pellisier granite (Analysis No. 5), it is 4.45 per cent. In a relatively unaltered phyllite (Analysis No. 7), it is 5.56 per cent. In a schist about a mile from an exposure of Boundary Peak granite, it is 7.72 per cent (Analysis No. 9). In argillites overlying the Pellisier granite, at 9150 feet in Indian Canyon (about half a mile from an exposure of Boundary Peak granite), it is 9.23 per cent. In an argillite almost vertically above (2000 or 3000 feet) the Boundary Peak granite, it is 12.41 per cent (Analysis No. 34). In a partly recrystallized schist (Analysis No. 8), it is 17.96 per cent. In a highly albitized Pellisier granite, in contrast, it is 1.14 per cent (Analysis No. 24).

The zonal distribution of the iron of the sediments and the contact region needs neither microscope nor analyses for its determination. In most of the specimens in the field, the iron minerals are megascopically visible under the hand lens.

Possibly, the iron may have been derived from the magma, but, in view of the low iron content of the Boundary Peak granite and of the existence in most places on an iron-poor zone immediately adjacent to the granite, it is no less reasonable to believe that it may have been concentrated from the sediments being dissolved, transported, and reprecipitated by circulating solutions derived from the magma or activated by heat from that source.

FIGURE 1. CANYON WALL
Section shown diagrammatically in Figure 8. Illustrating intermediate stage in granitization of the schist. The groundmass closely resembles granite but contains much biotite. The schist fragments (just above the center and to the right) have parallel orientation. Potash feldspar metacrysts are 1 to 3 inches across.

FIGURE 2. ALBITE VEINS IN GRANITE
Glacial cirque, Davis Canyon. Veins are from 1 to 2 inches wide.

FIGURE 3. MIGMATITES
From the contact zone between Boundary Peak granite and sediments.

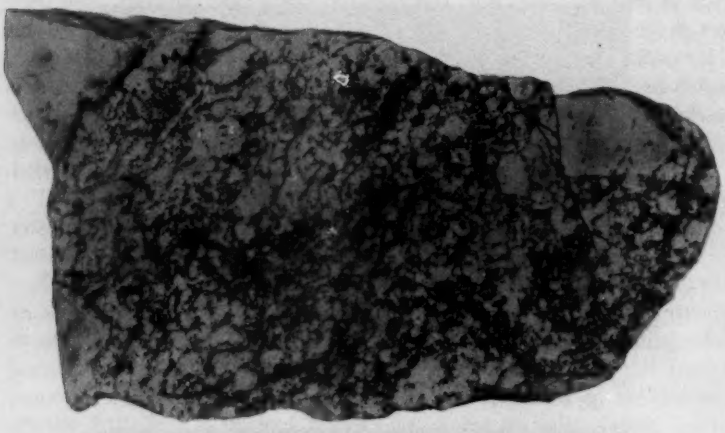

FIGURE 1. TEXTURAL FEATURES OF GRANITE
In fairly advanced stage of formation by replacement of schist. Thin shreds of schist are preserved in the groundmass in parallel orientation (lower left to upper right). In the upper right is a large potash-feldspar metacryst; smaller metacrysts are scattered through the mass. About ½ natural size.

FIGURE 2. ADVANCED STAGE OF GRANITIZATION
Further advance of the process illustrated in text Figure 4 and Plate 3, figure 3. Clusters of potash-feldspar metacrysts are enclosed in granite groundmass. The dark patches (lower left) are probably almost completely digested xenoliths. Note concentric inclusions of biotite in the metacrysts.

ADVANCED STAGES OF GRANITIZATION

Irregularities in the iron distribution in the sediments may also be due partly to the presence of the meta-basalts.

COMPLICATIONS IN THE CONTACT ZONE

General statement.—In studying gradational or transitional contact zones of the kind just described, it might be considered possible, at first thought, to trace, step by step, the various textural, mineralogical, and chemical changes from meta-sediments to granite. The logical procedure would be to begin either with the granite or with the meta-sediments and take samples at stated intervals across the contact zone, from one rock to another. From the study of these samples and their change of composition, it should be possible to form conclusions as to the loss or gain of material through metasomatic processes and as to the degree of recrystallization at different distances from the intrusive.

Practically, however, in studies of this kind, many difficulties are encountered, and contradictory results are often obtained. Most important complicating factors are:

(1) Initial variations in the composition of both sediments and the granite.
(2) The influence of structural control.
(3) Repeated movements of the magma, with consequent overlapping of metamorphic effects.
(4) Intense development of later pegmatites and aplites in the contact zone, with accompanying changes.
(5) Alterations by end-stage emanations from the magma, such as silicification and albitization, superimposed upon earlier changes.
(6) Three-dimensional relations between country rock, magma, and surface.

Variations in composition of sediments and granite.—Sediments vary greatly in mineralogical and in chemical composition, along the strike as well as across it. This is due partly to differences in the conditions under which they accumulate and partly to differences in source materials. This is particularly true of terrestrial deposits, as Walcott considered most pre-Cambrian sediments to be.[34] Within a mile, or less, the differences in silica or iron content, for example, along a single bed may amount to several per cent. Changes brought about by regional metamorphism may increase these differences.

Similarly, even fairly homogeneous granite, such as the Boundary Peak granite, exhibits considerable difference in composition in outcrops only a few hundreds of yards apart. These variations are not as great as in the sediments, but they may be important, especially in comparing such components as ferric oxide or soda or potash. In such a rock as the Pellisier granite, the variability is much higher.

[34] Adolph Knopf and Edwin Kirk: *A geological reconnaissance of the Inyo Range and the eastern slope of the Sierra Nevada, California*, U. S. Geol. Surv., Prof. Pap. 110 (1918) p. 23.

It is evident, therefore, that changes in composition across the contact zone may not be due entirely to introduction of magmatic material but, also, at least in some degree, to changes in the initial composition of the sediments. Conclusions based upon such data might be wholly unreliable.

Influence of structural control.—It is to be expected that alterations produced by magmatic emanations in a contact zone will be most intense in the vicinity of joints, faults, and other channel-ways. Similarly, bedded or foliated rocks, with planes of bedding or schistosity dipping into the intrusive, will be altered for greater distances from the intrusive than those in which these structures dip away from the granite. In a strongly altered area in which adjoining fault blocks have been rotated differently in respect to each other, structural control is likely to produce great irregularities in contact alteration.

Overlapping metamorphic effects.—As the metamorphism of rocks depends partly upon temperature and pressure and partly upon chemical reactions between the solid rocks and the circulating solutions, it should be possible, in a region of fairly homogeneous country rocks, to work out various zones of contact metamorphism, at increasing degrees of metamorphism. Goldschmidt has attempted to do this in his study of the Kristiania region.[35] Unfortunately, the lack of uniformity in composition and in structure in most places prevents such precise determinations. A further complication is introduced by changes in position of the magma.

As already stated, a magma is intruded not as a continuous process but rather as a series of movements, separated by more or less prolonged pauses. Batholithic intrusion is related to tectonic movements, and these movements are intermittent. The effects of regional and contact metamorphism may be superimposed upon each other. Moreover, as Cloos and others have shown, the entire batholith does not move at once, but various parts move at different times, just as in a fault zone, such as the one bordering the eastern slope of the Sierra Nevada, displacements occur at different times along the zone. Thus, an overlapping or telescoping of effects may be produced within any part of the contact zone. Complications of this sort cannot be determined by examination of the surface.

Intensive development of pegmatites and aplites.—Numerous pegmatites and aplites are found in the contact aureole of the Boundary Peak granite. In places, they form a veritable network of dikes and veins. They were probably formed late in the development of the contact zones.

[35] V. M. Goldschmidt: *Die kontaktmetamorphose in Kristianiagebiet* (1911) Kristiania.

Unquestionably, the pegmatites, especially, have to some degree modified the composition of the rocks they cross,[36] for not only do they rarely have definite walls, but, commonly, large crystals of the minerals composing it are found, decreasing in number and size, in the host rock, for tens, or even hundreds, of feet from the pegmatite proper.

Alterations by end-stage emanations from the magma.—Both the Pellisier granite and the other rocks of the contact zone show evidence of having been more or less profoundly altered by end-stage magmatic emanations. This is also true of the marginal parts of the Boundary Peak granite. The alterations are chiefly albitization and silicification. The latter has chiefly affected the limestones. The Pellisier granite and many of the contact rocks have been albitized, to degrees varying from place to place, depending upon structural and compositional differences and upon position in relation to the Boundary Peak mass. In general, the rocks overlying the Boundary Peak mass are more strongly albitized than are those upon its flanks. The mineral chiefly affected is potash feldspar. Other important mineralogical changes, however, accompany the albitization.

Relations between country rock, magma, and surface.—In any study of contact zones, possible complications, produced by subsurface conditions, must be kept in mind. These can best be explained with the aid of diagrams.

Figure 4 shows typical surface exposures in the northern Inyo Range. In the absence of any of the other complications, samples taken at *A, B, C, D,* and *E* might reasonably be expected to exemplify the successive stages in the change from sediments to granite.

The subsurface conditions, however, may actually be as shown in Figure 5, or they may be even more complicated, as shown in Figure 6.

It is obvious that samples taken at *A, B, C, D,* and *E* of Figures 5 and 6 do not represent progressively increasing effects of the heat, pressure, and emanations from the granite upon the meta-sediments.

The contact zones, which present puzzling and contradictory phenomena, must be discussed in general terms.

DIFFERENCE IN CONTACTS PHENOMENA

As already pointed out, alterations of meta-sediments and associated rocks overlying the Boundary Peak granite differ in kind and in intensity from those affecting the rocks on the flanks of the intrusive. In the roof rocks, recrystallization and replacement are, as a rule, more nearly complete. Albitization and silicification are the most important chemical

[36] J. F. Kemp: *The pegmatites,* Econ. Geol., vol. 19 (1924) p. 711-712.

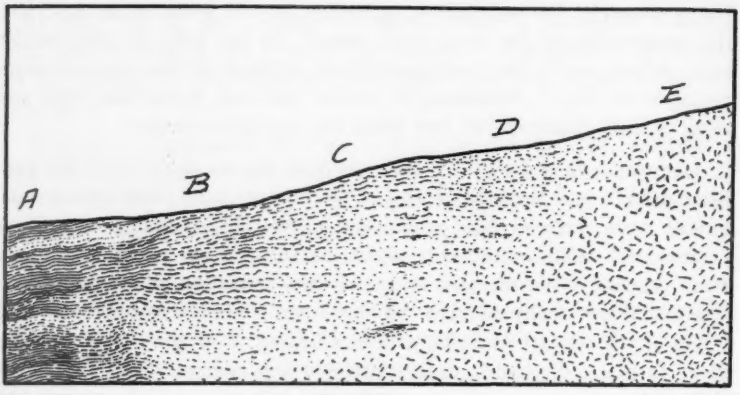

FIGURE 4.—*Diagrammatic section showing ideal transition from meta-sediments to intrusive*

Specimens collected at *A*, *B*, *C*, *D*, and *E* should show successive changes in composition. Such gradational transitions are rarely, if ever, found.

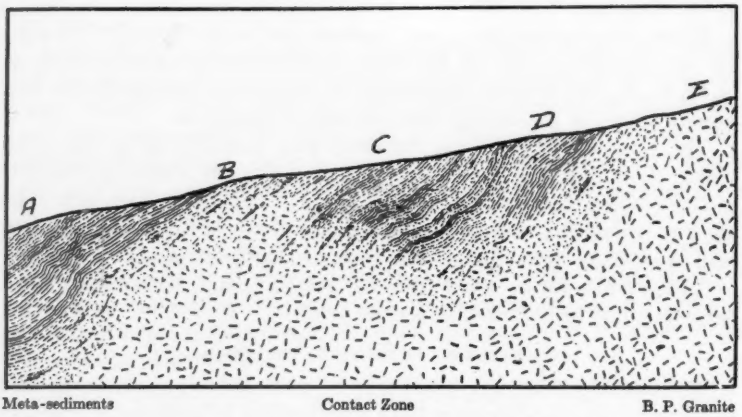

FIGURE 5.—*Diagrammatic section showing common sub-surface relations between intrusive and country rock*

True granite is exposed only at *E*, but specimens collected at *A*, *B*, *C*, *D*, and *E* do not show gradational changes in composition from country rock to granite.

changes. In the rocks flanking the intrusive, on the contrary, recrystallization is less pronounced. Silicification is important in places, especially in limestones or calcareous shales, but the most common chemical change is the introduction of potash, ordinarily evidenced by the formation of orthoclase metacrysts and of sericite.

It must be understood, however, that these are generalizations, to which many exceptions are found. So many complicating factors exist that no absolutely invariable rules can be laid down.

PROPORTION OF MATERIAL DERIVED FROM MAGMA

The amount of material obviously of magmatic derivation in the contact zones varies greatly from place to place. In some localities, recrystallization is the principal alteration. All stages are found, from slight to nearly complete. Even where orthoclase metacrysts are abundant, these may have been formed partly of materials already present in the sediments. Elsewhere, however, magmatic materials have been added in large amounts. Where albitization and silicification have taken place on a large scale, the soda and silica probably were introduced, for the unaltered meta-sediments in the vicinity are relatively low in both these substances.

PROCESS OF ADDITION OF MATERIAL

The writer believes that the addition of material in the contact zones was mostly by replacement. No field evidence has been found indicative of increase in volume or in density of the mixed rocks. The new minerals appear to have formed by replacing the old—the contacts between them are nearly everywhere indicative of corrosion (Pl. 4, fig. 1; Pl. 10, fig. 3; Pl. 7, figs. 2 and 3).

In many instances, however, the replacements are not direct. For example, where soda replaces the potash in orthoclase to form albite, the potash may go in part to form sericite in plagioclase by replacement of calcium. The calcium, in turn, may be used in part in the formation of epidote. Thus, some of the chemical, as well as the mineralogical and textural, changes are complex (p. 50-56).

Even where comparatively little material is added from the magma, complex reactions may occur. An example is the probable formation of metacrysts of orthoclase and plagioclase, in part by recombinations of materials already present in the sediments. This development can be distinctly traced in a series of sections prepared from samples collected in the contact zones. In initial stages, the metacrysts can be seen as "skeleton" or "ghost" crystals, of rather hazy appearance and ragged outline, which appear to have grown by reacting with, and absorbing much of, the neighboring or included groundmass (Pl. 4, fig. 2). With

continued growth of the metacrysts, the proportion of groundmass is reduced until, in the end-stage, the rock megascopically and microscopically is virtually indistinguishable from a true granite. If the metacrysts are large (porphyroblasts) and of orthoclase, they commonly include biotite, quartz, and plagioclase from the groundmass, either in concentric or in helezitic arrangement. Where remnants of the groundmass persist in the areas between the metacrysts, the texture

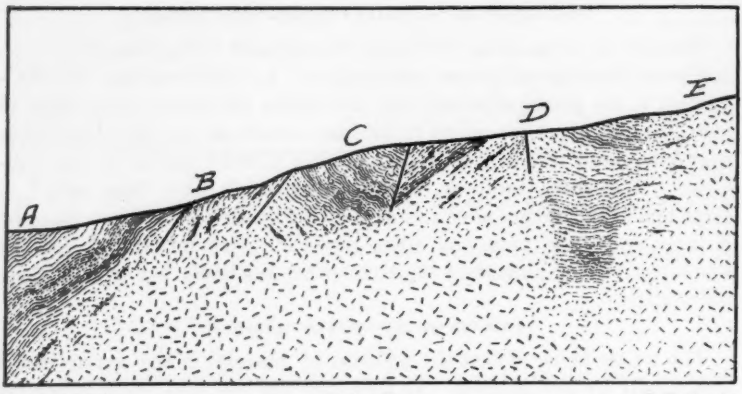

FIGURE 6.—*Diagrammatic section showing complicated sub-surface relations between granite and country rock due to pre-intrusive faulting*

A specimen collected at *B*, for example, would be more strongly affected by contact metamorphism than one collected at *C*, which is nearer a surface exposure of true granite.

closely resembles the pseudo-cataclastic texture hereinafter described (p. 53). The similarity is, indeed, so great that the writer has been led to question whether that texture may not have been produced as well by a corrosion of the groundmass by the larger crystals as by the reverse of that process.

The metacrysts may be potash or plagioclase feldspar or quartz.

The albitization of potash feldspar metacrysts probably took place before the complete conversion of the sediments to granite. Nearly everywhere, they are to some degree albitized, and more or less albite is to be found in the groundmass of all the contact rocks. Generally, though not invariably, the closer geographically the meta-sediments are to the true igneous rock the more highly they are albitized. Still more striking is the increase in intensity of albitization near the apex of the batholith.

SPECIFIC EXAMPLES OF CONTACT PHENOMENA

The contact zones, for reasons already discussed, are so complex in detail that no single occurrence can be selected to illustrate all variations. The alteration of the rocks lying above the summit of the Boundary Peak granite can best be observed in the upper parts of Leidy Canyon or Perry Aikin Canyon or in Indian Canyon, west of the McNett ranch.

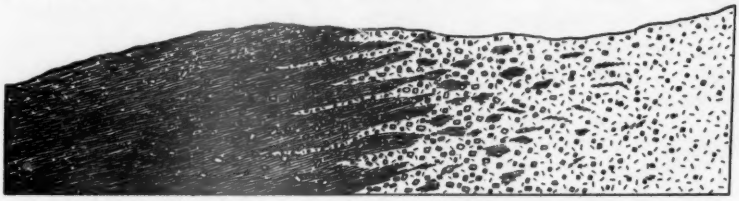

FIGURE 7.—*Diagrammatic sketch of relationship between granite and schist in unnamed canyon north of Leidy*

Sketch represents a section of the canyon wall, about a mile long. Porphyroblasts, shown greatly exaggerated in size, are of potash feldspar. Orientation of the schist xenoliths is parallel to that of the main body of schist.

Alteration of the rocks flanking the batholith can be observed in Montgomery Canyon, Morris Canyon, or, on the east side of the range, in Toler Canyon, McAfee Canyon, or some of the unnamed canyons in that vicinity.

From Montgomery Peak north, the Boundary Peak granite rises to the crest of the range. Between Indian (McNett) Canyon and Montgomery Peak the crest is chiefly of Pellisier granite and closely related rocks. From Indian Canyon south to White Mountain Peak, more or less completely altered and recrystallized quartzites and meta-basalts form the crest. In general, from north to south the Boundary Peak granite is exposed at lower and lower elevations. Structural complications, however, provide exceptions to this rule.

Successive stages in the transition from biotite schist to porphyritic granite are especially clear in the canyon just north of Leidy Canyon, on the east side of the range. The relationships are shown in Plate 5, figure 1, Plate 6, and diagrammatically in Figure 7.

The process begins with the formation of large metacrysts (porphyroblasts) of potash feldspar within the schist. In the locality just mentioned, many of the metacrysts (porphyroblasts) are more than an inch across. They invariably enclose residual portions of the groundmass, chiefly biotite and other ferromagnesian minerals.

In the earliest stage, the groundmass between the large crystals is slightly altered schist. As a second step, in some instances, the biotite

becomes bleached to a sericite-like mica, which makes up a large part of the rock.

Granitic material is introduced into the still-schistose groundmass, as sinuous bands consisting mostly of quartz and feldspar along the foliations. Continuation of the process is accompanied by a reduction in the proportion of biotite. As replacement proceeds, the pattern comes to consist of elongated inclusions and "stringers" of schist, abundantly distributed through an essentially granite matrix. The porphyroblasts appear not to have been affected by later replacements and persist to the end of the process. In intermediate stages, the feldspar porphyroblasts are here and there found upon the boundary between granite matrix and schist inclusions, enclosed partly in one and partly in the other.

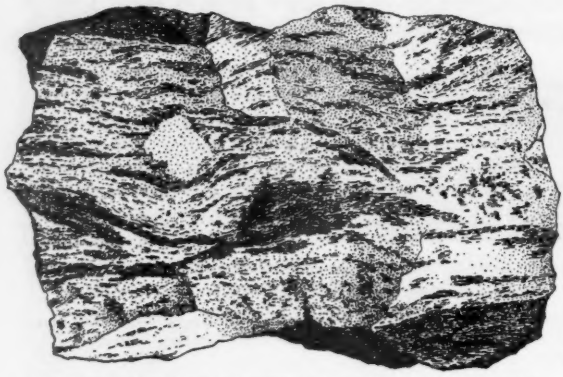

FIGURE 8.—*Detail of structure of partly granitized schist*

Large light-colored grain is a potash-feldspar metacryst. Drawing of actual specimen, about ⅔ natural size.

In the final stages of the replacement, the schist xenoliths disappear or become indistinguishable, and the rock is, to all appearances, a porphyritic granite with large phenocrysts, which commonly enclose biotite and quartz. A granite of this type is widespread in the northern Inyo Range.

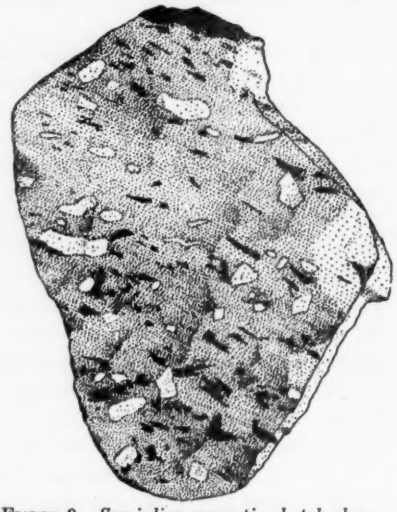

FIGURE 9.—*Semi-diagrammatic sketch showing beginnings of recrystallization of argillite*

Light-colored grains are potash feldspar metacrysts; dark material is chiefly biotite. About ⅔ natural size.

CHEMICAL CHANGES ACROSS CONTACT ZONES

Samples were taken across the transition zones, from sediments to granite, along lines approximately perpendicular to the trend of the contact in three localities. Three samples were chosen for analysis from one of these zones and two from each of the others. The results are suggestive but, as is to be expected, not entirely consistent.

The first series represents the transition, within a distance of about half a mile, from a biotite schist to a marginal facies of the Boundary Peak granite having the mineralogical composition of a granodiorite. The locality is the south branch of Indian (McNett) Canyon.

Granitic juices appear to have been introduced along the planes of schistosity, producing reactions with the country rock (p. 25).

Analysis No. 8 (Table 3) is of comparatively uncontaminated biotite schist.

Analysis No. 10 (Table 3) is of the same rock, into which a rather large proportion of material appears to have been introduced from the magma; it contains quartz, zoned plagioclase, biotite, titanite, some epidote, and a comparatively small amount of potash feldspar. The plagioclase is oligoclase. The biotite, part of the quartz and feldspars, and the opaque minerals comprise a groundmass in which are set larger grains of feldspar, including the zoned plagioclase, and quartz. The biotite has parallel orientation and apparently is like the biotite of the schist. The entire groundmass resembles the schist. Where the potash feldspars are bordered by groundmass, the latter is fringed with myrmekites (Pl. 9, fig. 2; Pl. 7). These are abundant throughout the rock. Nearly all potash feldspars are partly albitized. The central parts of the zoned plagioclases are highly altered to white fibrous mica, but, in general, the feldspars are comparatively little clouded. The texture is peculiar, suggestive of one produced by a series of complex replacements. The rock contains many small schist xenoliths (Fig. 9).

Analysis No. 11 (Table 3) is of rock that nearly resembles a true granite. The mineralogical composition is essentially the same as that of a following sample (Analysis No. 22), but the xenoliths are more nearly completely digested and are less readily distinguished as such. Under the microscope, however, shreds and fragments of partly assimilated schist are readily discerned. These changes, though to some degree dependent upon differences in the composition of the sediments involved, are probably fairly characteristic of this type of granitization.

Analyses No. 12 and No. 13 illustrate a second type of alteration without megascopically visible penetration of granitic material into the sediments (p. 25). Both are of rocks from the argillite-granite contact zone in upper Indian Canyon. The two samples were collected from points about a mile apart, but the difference in proximity to the granite below the surface is probably not nearly so great.

Analysis No. 12 (Table 4) is of a dense bluish-gray rock from the zone of maximum iron concentration. It consists of fine-grained quartz and feldspar (almost entirely albite) and much magnetite and hematite. Larger grains of chess-board albite are scattered through the groundmass.

Analysis No. 13 (Table 4) is the same rock, more altered and recrystallized (Pl. 3, fig. 3). Metacrysts of albite and potash feldspar, partly albitized, are distributed abundantly through a fine-grained groundmass containing quartz, albite, and biotite, with a small proportion of iron oxides.

TABLE 3.—*Changes in composition of biotite schist produced by granitization*

(Ed Eisenhauer, Jr., Los Angeles, analyst; computations by R. P. Bryson, California Institute of Technology)

Constituents	Analyses			Constituents in grams/100 cc			Gain or loss in grams of each constituent		Gain or loss in percentage of original mass of each constituent		Gain or loss in percentage of total original rock mass		Recalculations of analyses on assumption that Al_2O_3 has remained constant	
	(8) Biotite schist comparatively uncontaminated	(10) Biotite schist into which considerable magmatic material has been introduced	(11) Biotite schist almost completely recrystallized or "granitized"	(8a) Uncontaminated biotite schist	(10a) Partly granitized schist	(11a) Almost completely granitized schist	(10b) Partly granitized schist	(11b) Almost completely granitized schist	(10c) Partly granitized schist	(11c) Almost completely granitized schist	(10d) Partly granitized schist	(11d) Almost completely granitized schist	(10e) Partly granitized schist	(11e) Almost completely granitized schist
SiO_2	42.50	56.74	63.20	125.0	155.	171.3	+30.	+46.3	+24.	+37.1	+10.3	+15.7	54.44	58.24
Al_2O_3	25.74	22.33	19.56	75.8	60.9	53.	−14.9	−22.8	−19.65	−30.1	− 5.06	− 7.75	25.74	25.74
Fe_2O_3 / FeO	17.96	8.57	5.94	52.9	23.4	16.1	−29.5	−36.8	−55.7	−69.6	−10.0	−12.5	8.19	5.47
MgO	3.88	1.94	1.07	11.44	5.3	2.9	− 6.14	− 8.54	−53.7	−74.7	− 2.08	− 2.9	1.85	.99
CaO	2.17	4.58	4.06	6.40	12.5	11.0	+ 6.1	+ 4.6	+95.3	+71.9	+ 2.07	+ 1.56	4.34	3.74
Na_2O	2.15	2.82	2.90	6.34	7.7	7.9	+ 1.36	+ 1.56	+21.4	+24.6	+ .46	+ .53	2.69	2.67
K_2O	4.76	2.06	1.61	14.03	5.6	4.4	− 8.43	− 9.63	−60.1	−68.6	− 2.86	− 3.26	1.97	1.48
Total	99.16	99.04	98.34	291.9	270.4	266.6	−21.5	−25.3			− 7.17	− 8.62	99.22	98.33
Sp. Gr	2.95	2.73	2.71											
Total alkalies	6.91	4.88	4.51											
Ratio Na_2O/K_2O	0.45	1.37	1.80											

TABLE 4.—*Chemical changes produced by magmatic emanation*

(Ed Eisenhauer, Jr., Los Angeles, analyst; computations by R. P. Bryson, California Institute of Technology)

Constituents	Analyses			Constituents in g/100 cc		Gain or loss in grams	Gain or loss in percentage		Recalculation of Analysis No. 13
	(14) Moderately albitized variety of Pellisier granite	(12) Dense, bluish-grey rock from quartzite-argillite-meta-volcanic series, probably a silicified and amphibolitized basalt or andesite	(13) Same as No. 12, but about one mile closer to Boundary Peak granite	(12a) Less altered rock	(13a) More altered rock	(13b) Of each constituent in alteration of 100 cc. of the original rock	(13c) Of original mass of each constituent	(13d) Of total original rock mass	(13e) Based on assumption that Al_2O_3 has remained constant at value given in Analysis No. 12
SiO_2	62.58	60.20	69.92	166.	185.3	+19.3	+11.6	+7.0	66.39
Al_2O_3	17.67	20.47	16.26	56.5	43.2	−13.3	−23.7	−5.0	20.47
Fe_2O_3	2.14	10.29	0.97	28.4	2.6	−25.8	−91.	−9.3	0.90
FeO	2.92	0.56	2.24	1.55	5.9	+ 4.3	+284.	+1.6	2.13
MgO	1.06	0.28	1.27	.77	3.4	+ 2.6	+338.	+0.9	1.21
CaO	3.80	1.05	1.97	2.9	5.2	+ 2.3	+79.3	+0.8	1.87
Na_2O	3.75	6.26	3.95	17.3	10.5	− 6.8	−39.3	−2.5	3.75
K_2O	4.79	0.72	2.98	2.0	7.9	+ 5.9	+295.	+2.1	2.83
TiO_2	.06	0.03	0.08	.1	.2	+ .1	+100.	+0.1	.08
MnO	0.05	0.03	0.02	.1	.1				.02
Total	98.82	99.89	99.66	275.6	264.3	−11.4		−4.4	99.65
Sp. Gr		2.76	2.65						
Total alkalies	8.54	6.98	6.93						
Ratio Na_2O/K_2O	0.78	8.69	1.33						

Analysis No. 14 (Table 9) is of the Pellisier granite, approximately half a mile from that whose composition is given in Analysis No. 13. It contains strongly albitized potash feldspar, plagioclase—partly altered to epidote and sericite (or paragonite)—considerable chlorite and bleached biotite, a rather small proportion of quartz, and free calcite, all in a pseudo-cataclastic groundmass. The epidote exceeds the sericite, and the initial potash feldspar probably greatly exceeded the plagioclase. The plagioclase is partly albitized in some rocks, and is much clouded both by finely divided epidote and by an opaque mineral. Iron oxides are fairly abundant. Pseudo-cataclastic texture is the predominant texture of the rock.

PEGMATITES AND APLITES

The margins of the Boundary Peak and the Pellisier granite and their associated contact rocks are crossed by numerous pegmatites and aplites. Some of these have fine-grained margins and coarse-grained centers. Many of the pegmatites are discontinuous, irregular bodies, apparently formed by replacement. The feldspars and quartz of the pegmatites are of the same structure and composition as are the corresponding wall-rock minerals. The aplites are mostly sharp-walled dikes, differing in composition from the including rock. The pegmatites have no definite borders; they consist chiefly of large crystals of feldspar, orthoclase, and accessory minerals. These large crystals of feldspar and quartz are found distributed throughout the neighboring country rock, decreasing in size and number with increasing distance from the pegmatite.

Two types of aplites have been distinguished; an earlier finer-grained sill-like variety, which follows the structure of the intruded rock, and a later coarser-grained type, which, in most cases, cuts obliquely across the earlier structures, normally without offsetting them.

Most of the pegmatites have graphic intergrowths of quartz and feldspar, both orthoclase and plagioclase. All of the quartz of a thin section of one of these rocks commonly has the same orientation (i.e., extinguishes simultaneously) whether enclosed in orthoclase or in plagioclase.

In many instances, the composition and the texture of the pegmatites change abruptly from one host rock to another. The difference is usually in the relative proportions of the different minerals and in the shape and size of the mineral grains. They terminate abruptly at the border between rocks of different types.

Tourmaline and other minerals commonly associated with pegmatites are rare in the northern Inyo Range.

The following analyses show the composition of average pegmatites and aplites from the northern Inyo Range.

Analysis No. 15 (Table 5) is of an aplite dike from an elevation of 9500 feet on the south side of Middle Canyon, about 5 miles west of the mouth of the canyon. It consists of fine-grained matrix of quartz, orthoclase, plagioclase, and iron oxides, through which are scattered numerous larger feldspar grains, most of them strongly

albitized. These larger grains have ragged borders; they appear to be relicts of an older granite. Both the orthoclase and the plagioclase of the matrix, on the contrary, appear fresh and unaltered.

Analysis No. 16 (Table 5) is of a dull-grey aplite in Pellisier granite near the crest of the range, northwest of Indian Canyon. It is composed chiefly of quartz

TABLE 5.—*Analyses of aplites and pegmatites*

(Ed Eisenhauer, Jr., Los Angeles, analyst)

Constituents	Aplites			Pegmatites			
	(15) Granite aplite in intermediate granite	(16) Aplite in Pellisier granite	(19) Average composition of 15 aplites (Compiled by R. A. Daly)	(17) Pegmatite in contact zone	(18) Pegmatite in Pellisier granite	(20) Average composition of 7 pegmatites (Compiled by Johannsen)	Average of 7 pegmatites
SiO_2	73.40	72.95	75.00	72.50	72.83	72.70	65.62 – 77.00
Al_2O_3	15.36	16.40	13.14	16.21	16.37	14.86	12.5 – 16.49
Fe_2O_3 } FeO	1.03	1.65	0.98	2.07	1.80	0.91	0.32 – 1.85
MgO	1.12	*	0.30	*	*	0.31	0.3 – 0.72
CaO	1.30	1.33	1.13	1.38	2.84	0.61	none – 1.17
Na_2O	3.21	3.63	3.54	3.42	2.72	2.80	1.89 – 4.20
K_2O	3.02	3.67	4.80	4.43	3.06	6.78	3.84 – 10.87
Total	99.34	99.63	98.89	100.01	99.62	98.97	84.47 – 112.30
Total alkalies	6.23	7.30	8.34	7.85	5.78	9.57	5.73 – 15.07
Ratio Na_2O/K_2O	1.06	0.98	0.73	0.77	0.88	0.41	0.49 – 2.38

* Not determined.

and potash feldspars streaked with albite ("streak perthites"), with a small admixture of iron oxides. The potash feldspars are dusty, but the albite areas are relatively clear.

Analysis No. 17 (Table 5) is of a pegmatite with large grains of potash feldspar and quartz in a finer-grained, seemingly altered matrix. The large feldspar grains are strongly perthitic, the intergrowths being of the "patch and vein" type. The groundmass contains microcline, oligoclase, muscovite, and a small amount of chlorite. The texture is pseudo-cataclastic.

Analysis No. 18 (Table 5) is also of pegmatite in the Pellisier granite with highly albitized potash feldspars. The feldspars of the pegmatite, on the contrary, are comparatively little altered, and the plagioclase is fresh in appearance. Quartz and feldspars are in a graphic pattern, apparently formed by replacement. The quartz is intergrown with both potash feldspar and plagioclase and, in numerous instances, either crosses the borders of the feldspar grains or lies between them.[37]

[37] Gilluly notes the similarity between graphic texture and myrmekite, and describes a gradation between them in the Sparta granite. He indicates a belief that some graphic textures may have been formed by replacement, and gives references to other authors who hold the same view. James Gilluly: *Replacement origin of albite granite near Sparta, Oregon*, U. S. Geol. Surv., Prof. Pap. 175 C (1933) p. 68, 72.

In parallel columns accompanying these analyses are given the average composition of fifteen granite aplites, (Analysis 19, Table 5) as presented by Daly,[38] and the average of seven analyses of granite pegmatites (Analyses 20, Table 5) listed by Johannsen.[39]

Both pegmatites and aplites are among the most variable of igneous rocks in mineralogical and chemical content. So far as averages may serve for comparison, both the aplites and the pegmatites given in Table 5 appear to be more sodic than the average. The mean of the soda/potash ratios for the aplites is 1.02, as compared with the average of 0.73; that of the two pegmatites is 0.82, as compared with 0.41 for the average.

ALBITE-RICH BODIES IN META-SEDIMENTS

Of especial significance are the albitite bodies in the argillites near the intrusive contacts. These bodies, irregular in shape and varying in size from a few feet to hundreds of feet in cross-section, are commonly found a short distance above the batholithic roof, just east of the crest of the range. They are especially well exposed in the steep walls of the ancient cirques at the heads of Indian and Leidy canyons, but their relation to the main batholith is invariably concealed by talus. In some instances, they appear to be sills, but, more commonly, they are cross-cutting structures. Their buff tint is in marked contrast to the prevailing bluish-grey of the argillites; this renders them easily distinguishable from a distance.

The albitite bodies may be cupolas of the batholith, but it is much more probable that they were formed by replacement of the sediments. The chess-board structure of the albite, as well as the proximity of the bodies to igneous rocks in which albitization of the potash feldspars has manifestly taken place on a large scale, indicate that they owe their origin to the same solutions that altered the Pellisier granite.

The formation of these albite-rich bodies is thought to have taken place in two stages. In the first stage, recrystallization and replacement of the argillites by heat, pressure, and solutions from the magma formed granite-like rocks, consisting chiefly of plagioclase, orthoclase, quartz, and biotite. In the later stage, soda-rich end-stage emanations from the Boundary Peak granite almost completely replaced the feldspars with albite, removed the biotite or converted most of it to chlorite, and enriched the rock in quartz. The intensity of alteration is probably to be ascribed to the location of these rocks above cupolas of the batholith.

Analysis No. 21 (Table 6) is of a sample from one of the albite bodies above the batholith. The rock contains "chess-board" albite, quartz, a little bleached biotite and chlorite, a few small grains of titanite, and a small amount of magnetite dust.

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[38] R. A. Daly: *Igneous rocks and their origin* (1918) p. 35.

[39] Albert Johannsen: *Descriptive petrography of the igneous rocks*, vol. II (1932) p. 75. Chicago.

The feldspars are only slightly clouded. Approximately 65 percent of the rock is "chess-board" albite and about 30 percent, quartz.

Analysis No. 22 (Table 6) is of an albite-rich body at an elevation of 11,000 feet in Indian Canyon. The rock consists almost exclusively of albite and quartz, with some magnetite and titanite associated with the albite. It appears to have undergone

TABLE 6.—*Chemical composition of albite-rich bodies in roof of batholith*

(Ed Eisenhauer, Jr., Los Angeles, analyst)

Constituents	(21) Albite body above the batholith	(22) Albite-rich body, Indian Canyon, elevation 11,000 ft.
SiO_2	71.84	69.95
Al_2O_3	15.85	18.21
Fe_2O_3, FeO	1.90	2.49
MgO	0.85	tr.
CaO	0.98	1.45
Na_2O	5.81	5.99
K_2O	1.11	1.63
TiO_2	0.09	
Total	98.43	99.72

some crushing, as is indicated by fractured grains of feldspar, bent and broken twinning lamellae, and some shredding of the quartz, with accompanying mortar texture.

If it is assumed that the soda is all contained in albite and the potash all in orthoclase, the percentage of each of these minerals is as shown in Table 6.

ORIGIN OF THE PELLISIER GRANITE

SUMMARY AND DISCUSSION

The writer believes that the Pellisier granite was formed *in situ*, partly by recrystallization and partly by replacement of older rocks of both sedimentary and igneous character. Heat, pressure, and solutions necessary for the transformation are thought to have been derived chiefly from the magma from which the Boundary Peak granite was crystallized. The end-stage emanations from the magma in some degree albitized the uppermost parts of the Boundary Peak mass (Analyses Nos. 1, 2, 25, 26), these portions having crystallized before the complete solidification of the deeper parts of the batholith.

The hypothesis concerning the origin of the Pellisier granite is based, in part, upon the similarity in composition and texture between it and

the partly recrystallized and replaced rocks of the contact zone, and, in part, upon other evidence, which is summarized as follows:

(1) The contacts between the older rocks and the Pellisier granite are nearly all gradational, whereas those between the Boundary Peak granite and the Pellisier granite are like those between the Boundary Peak granite and the sediments. Textural and compositional peculiarities of the Pellisier granite can be traced in various stages of development through the contact zones, where they are, in places, fully as prominent, or even more prominent, than in the granite itself. In the field, it is possible in many places to walk directly from granite to older rocks without finding any sudden change in the character of the rocks.

(2) Schist and argillite xenoliths in various stages of digestion are abundant throughout most of the Pellisier granite. In some areas, they have lost their sedimentary character and are almost completely digested. The xenoliths increase in number and size as the contacts are approached. The Boundary Peak granite, on the other hand, is nearly free from xenoliths.

(3) The Pellisier granite is variable, both in texture and composition. This is obviously to be expected in "igneous" rocks formed by granitization, partly because of the variability of the sediments from which they may have been derived. The Boundary Peak granite, as has already been pointed out, is of nearly uniform composition.

(4) In many places, the Pellisier granite has a structure closely resembling stratification in sedimentary rocks. The scale of the structure in most exposures is so large that it can be seen only from a distance. It may be due to differences in color or in hardness of alternating "layers" of granite, to the presence of prominent nearly horizontal joint planes, to differences in texture, or to other causes (Pl. 2, fig. 1). In other localities, minor structures of this sort are parallel to similar structures in sediments or in the xenoliths. Here and there, they can be traced directly into them (p. 10).

(5) The peculiar bluish-grey of the Pellisier granite closely resembles that of the argillites in the areas in which the two are in proximity. This is important only because in both cases the color is probably due to the same cause. It is apparent from microscopic observations and analyses that the grey tint of both sediments and granite is caused by finely disseminated ferruginous material, chiefly hematite, or, less abundantly, magnetite.[40] In the schists and argillites, the ferruginous ma-

[40] Tyrrell observed that the presence of dust-like inclusions gave a bluish tinge to plagioclase phenocrysts in a hornfelsed porphyry from Benguella. [G. W. Tyrrell: *A contribution to the petrography of Benguella*, Royal Soc. Edinburgh, Tr., vol. 51 (1916) p. 544.] Richey and Thomas also found that the clouding of feldspars in gabbros gives to the rocks concerned a peculiar black or bluish-black hue. [J. E. Richey and H. H. Thomas: *Geology of Ardnamurchan, northwest Mull and Coll*, Geol. Surv. Scotland, Mem. (1930) p. 238.] *See also* A. G. McGregor: *Clouded feldspars and thermal metamorphism*, Mineral. Mag., vol. 22 (1931) p. 524-538.

terial is scattered in a fine dust throughout the groundmass; in the granite, it is in a fine state of division in the feldspars and quartz. Chemical analyses of potash feldspar grains separated from the granite show an Fe_2O_3 content averaging 2 per cent or more.

(6) As the biotite schists are approached, the mafic content (mostly biotite) of the granite usually definitely increases and xenoliths become more numerous. In some instances, there is also a decided decrease in quartz.

(7) In some contact zones, relicts of replaced and partly digested meta-sediments can be traced directly into the rocks from which they were derived. The initial structural orientation generally appears to have been little, if at all, changed. Whether or not recrystallization and replacement of sediments is demonstrable as an origin for the entire body of Pellisier granite, the importance of the process in the contact zones is almost beyond question.

(8) Staurolite and sillimanite have been recognized in sections of the Pellisier granite from various localities.

At the outset of the investigation, the writer failed to recognize that the Pellisier granite was probably formed *in situ* by the granitization of older rocks rather than by crystallization from a magma. He was, in fact, distinctly skeptical of the theory that certain granites might have been formed in this way. Prolonged study in field and laboratory, however, convinced him that this hypothesis was the only one that satisfactorily explained all that he had observed in his study of the rocks of the northern Inyo Range.

The Boundary Peak granite presents no peculiarities that would indicate that it was formed in any way other than by the ordinary course of crystallization from a granite magma. Deuteric reactions have modified the margins, especially the upper one, but the mass as a whole shows no unusual features.

Granitization has never been precisely defined. In a narrow sense, it should relate only to the formation of a granite, but, as, theoretically, rocks formed by replacement and recrystallization may have the composition of monzonites, granodiorites, diorites, or gabbros, the term might well be extended to these. This would avoid such cumbersome terms as "granodioritization" or "gabbroization."

Used in this sense, granitization is a complex process, involving both recrystallization of sedimentary materials under the influence of elevated temperatures and pressures, and reactions between those materials and emanations introduced, possibly often in comparatively small amounts, from a subjacent magma. Reactions and recrystallization doubtless continue concurrently.

TABLE 7.—*Comparison of chemical composition of Pellisier granite and original rocks*

(Ed Eisenhauer, Jr., analyst; computations by R. P. Bryson, California Institute of Technology)

Constituents	Analyses			100 cc rock Constituents in grams of Consittuents in grams of			Gain or loss of each constituent necessary to convert original rock to granite				Gain or loss in percentage of total original mass of rock in conversion to granite		Recalculations of Analysis No. 5 on assumption iof tock in converson constancy of AlO_1	
							In grams (for 100 cc original rock)		In grams (for 100 cc In percentage					
	(5) Typical Pellisier granite	(7) Phyllite from crest of range, 4 miles N.W. of White Mountain Peak. 2 miles from surface exposures of Boundary Peak granite	(9) Quartz-biotite schist, somewhat contaminated by magmatic material. From south branch of Indian (McNett) Canyon	(5a) Granite	(7a) Phyllite	(9a) Schist	(7b) Phyllite	(9b) Schist	(7c) Phyllite	(9c) Schist	(7d) Phyllite	(9d) Schist	(7e) Phyllite	(9e) Schist
SiO_2	69.81	67.58	63.71	185.1	185.1	177.1		+ 8.0		+ 4.5		+ 2.9	67.06	67.55
Al_2O_3	16.57	19.82	19.25	43.9	54.3	53.5	−10.4	− 9.6	−19.1	−17.9	− 3.8	− 3.5	19.82	19.25
Fe_2O_3 } FeO }	4.45	5.66	7.72	11.8	15.5	21.5	− 3.7	− 9.7	−23.9	−45.1	− 1.4	− 3.5	4.27	4.31
MgO	0.46	1.19	1.20	1.2	3.3	3.3	− 2.2	− 2.1	−66.7	−63.7	− 0.8	− 0.8	0.44	0.45
CaO	2.80	1.45	1.80	7.4	4.0	5.0	+ 3.4	+ 2.4	+85.0	+48.0	+ 1.2	+ 0.9	2.69	2.71
Na_2O	2.70	1.65	2.83	7.2	4.5	7.9	+ 2.7	− 0.7	+60.0	− 8.6	+ 1.0	− 0.3	2.59	2.61
K_2O	2.47	2.20	2.03	6.6	6.0	5.6	+ 0.5	+ 1.0	+ 8.3	+17.7	+ 0.2	+ 0.4	2.39	2.39
TiO_2	0.17		0.07	0.5		0.2		+ 0.3		+150.0		+ 0.1	0.16	0.16
Ignition Loss			1.42											
Total	99.43	99.55	100.03	263.7	272.7	274.1	− 9.8	−10.4			− 3.6	− 3.8	99.42	99.43
Sp. Gr	2.65	2.74	2.78											

An attempt should be made to distinguish between assimilation and granitization. In the first of these, magmatic fluids are in excess and dissolve or absorb sedimentary rocks (which may, or may not, be in the form of fragments broken off from the main mass by stoping or by some similar process) either by "melting in" or reacting with them before crystallization. In the other, the granite is formed in place, by reactions between magmatic fluids and the solid minerals of the sediments. Solution and recrystallization go on concurrently; no large part of the mass is liquid at any given time; most of the magmatic emanations, in fact, may be gaseous. The amount of material added from the magma may actually be relatively small, so that the process may be only in part replacement.

The writer believes that assimilation and granitization go on together. As the magma advances, blocks of the country rock are broken off and fall into the liquid mass, where they melt or are assimilated by reaction with the fluid mass.[41] At the same time, the heat and pressure of the magma cause a partial or a complete recrystallization of the rocks forming the walls and roof of the intrusive. This process may be accompanied and complicated by reactions between the solid country rocks and the emanations, which may penetrate for distances of hundreds, or thousands, of feet from the intrusive, depending upon physical and structural conditions. These reactions are probably not unlike those that, according to Bowen, occur between the liquid magma and the xenoliths.

CHEMICAL CHANGES NECESSARY FOR GRANITIZATION

A comparison of the composition of the comparatively unaltered sediments with that of the typical Pellisier granite shows how relatively slight may be the chemical changes necessary for the conversion of the one into the other. Analysis No. 7 (Table 7) is of a phyllite obtained from a point as far as possible from a contact zone; Analysis No. 5 (Table 7) is of that part of Pellisier granite that most nearly resembles a true granite. The comparison is suggestive rather than direct, because the samples analysed were taken from points several miles apart, in which distance the composition of even an unaltered sediment might show considerable change.

The change in Na_2O is not significant in this connection, because the potash feldspars of the granite have been partly albitized, and the granite has, therefore, been enriched in soda since it was formed. These differences are no greater than corresponding differences between the compositions of two samples of Pellisier granite or even of other granites, several miles apart, and, certainly, they are less than the variations in

[41] N. L. Bowen: *The behavior of inclusions in igneous magmas*, Jour. Geol., vol. 30 (1922) p. 513-570; *The evolution of the igneous rocks* (1928) p. 175-228. Princeton.

the composition of sediments shown in distances of several miles along the strike. It is conceivable, therefore, that such a granite might even be formed from a member of this same group of sediments, without gain or loss of material.

A similar comparison may be made between the composition of the typical Pellisier granite and that of a quartz-biotite schist that lies nearer the granite than the phyllite of Analysis No. 7. The schist sample (Analysis No. 9, Table 7) is a composite sample and represents the average for its locality.

The relatively high soda content of the schist is probably due to addition of magmatic material. The soda/potash ratio is even higher in the schist than it is in the moderately albitized granite. Here, again, the comparisons indicate how slight are the chemical changes that may be necessary to convert a schist of this type into a granite.

The composition of the schist (Analysis No. 9) should be compared with that of the phyllite (Analysis No. 8, Table 3). As has been stated, the schist contains some material derived from the magma; that is, it is partly granitized. Too much weight should not, of course, be placed upon a single analysis.

ALBITIZATION AND RELATED PHENOMENA

MINERALOGICAL CHANGES

As has been emphasized, replacement processes are important in the history of the Pellisier granite. Whether or not the Pellisier was formed by granitization of sediments, there can be no doubt of the evidence of metasomatism. Throughout its mass, the granite exhibits peculiarities in texture and in composition, produced by interactions between fluids and the solid mineral grains. The granite may be regarded as the starting point or as the end-product of these processes. Unquestionably, it has been greatly altered by replacements.

The chief mineralogical changes include the albitization of the potash feldspars and some of the plagioclase feldspar; the conversion of biotite and other ferromagnesian minerals to chlorite; and the formation of sericite, epidote, and iron oxides, from materials set free during the alteration of the feldspars and the mafic minerals, or from elements introduced by the activating solutions from some outside source, or, most probably, from reactions between the two. It is likely that all these changes belong to a common series, each related in some way to all the others.

IMPORTANCE OF ALBITIZATION

The importance of albitization in the formation of metalliferous veins has been recognized for many years. Among the best known

studies of the process as it affects basic rocks are those by Bailey and Grabham [42] on the albitization of basic plagioclase feldspars, and by Dewey and Flett [43] on the British pillow lavas. Other descriptions have been published by Becke,[44] Geijer,[45] Sundius,[46] Shannon,[47] Fenner,[48] Reynolds,[49] and others. Grubenmann and Niggli have discussed albitization in basic rocks and their contact zones.[50]

Albitization of microcline has been described by various investigators including Becke,[51] Spencer,[52] Brøgger,[53] Landes,[54] Schaller,[55] Hess,[56] Colony,[57] Warren,[58] Gillson,[59] and Grubenmann and Niggli.[60]

Bailey and Grabham believed that the plagioclase of the spilitic lavas was albitized while the rocks were still hot and richly charged with volatile ingredients, and that the soda was derived, in each case, from the magma itself. They advanced the hypothesis that "in some volcanic centers . . . during crystallization of the lava an unusual portion of soda was thus retained in solution and that the residual liquors then began to react with the minerals which had been crystallized. . . . The lava at this stage was stewing in a concentrated solution of sodium carbonate." [61] Bowen, however, concluded that the albite of albite-bearing rocks of the Gowganda Lake district of Quebec was introduced by processes of replacement.[62] Most of the rocks are associated with

[42] E. B. Bailey and C. W. Grabham: *Albitization of basic plagioclase feldspars*, Geol. Mag. (1909) p. 250-256.

[43] H. Dewey and J. S. Flett: *On some British pillow lavas and the rocks associated with them*, Geol. Mag. (1911) p. 209.

[44] F. Becke: *Petrographische studient am tonalit der rieserferner*, Tschermaks Min. Pet. Mitt., vol. 13 (1892) p. 420.

[45] P. Geijer: *Geology of the Kiruna district*, vol. 2 (1910) Stockholm; quoted by U. Grubenmann and Paul Niggli, *Die Gesteinsmetamorphose*, vol. 1 (1924) p. 439.

[46] N. Sundius: *Beitrage zur geologie des sudlichen teiles des Kirunagebietes* (1915) Upsala; *Zur grage der albitisierungen*, Geol. Fören. Stockholm Förh., Bd. 38 (1916) p. 446.

[47] E. V. Shannon: *Mineralogy and petrology of intrusive Triassic diabase at Goose Creek, Louden Co., Virginia*, U. S. Nat. Mus., Pr., vol. 66 (1924) p. 83.

[48] C. N. Fenner: *The Wachtung basalt*, N. Y. Acad. Sci., Ann., vol. 21, no. 2 (1910) p. 121.

[49] S. H. Reynolds: *Igneous rocks of the Tortworth inlier*, Geol. Soc. London, Quart. Jour., vol. 80 (1924) p. 107.

[50] U. Grubenmann and Paul Niggli: *Die Gesteinsmetamorphose*, vol. 1 (1924) p. 220, 288, 290.

[51] F. Becke: *Zur physiographie der gemengteile der krystallinen schiefer*, Wien K. K. Akad. d. Wiss., Denkschr. 75 (1906).

[52] A. C. Spencer: *The Treadwell ore deposits*, U. S. Geol. Surv., Bull. 259 (1904) p. 74; *The Juneau gold belt*, U. S. Geol. Surv., Bull. 387 (1906) p. 211.

[53] W. C. Brøgger: *Die mineralien der syenitpegmatitgange der Sudnorwegischen augit- und nephelin-syenite*, Zeitschr. Krist., vol. 16 (1890) p. 559.

[54] K. K. Landes: *The paragenesis of the granite pegmatites of central Maine*, Am. Mineral., vol. 10 (1925) p. 373.

[55] W. T. Schaller: *Genesis of lithium pegmatites*, Am. Jour. Sci., 5th ser., vol. 10 (1925) p. 269-279.

[56] F. L. Hess: *The natural history of the pegmatites*, Eng. Min. Jour. Press, vol. 120 (1925) p. 293.

[57] R. J. Colony: *Final consolidation phenomena in igneous rocks*, Jour. Geol., vol. 31 (1923) p. 170-175.

[58] C. H. Warren: *Petrology of the alkaline granite and porphyries of Quincy and Blue Hills, Massachusetts*, Am. Acad. Arts Sci., Pr., vol. 49 (1913) p. 214.

[59] J. L. Gillson: *The granite of Conway, New Hampshire*, Am. Mineral., vol. 12 (1927) p. 316.

[60] U. Grubenmann and Paul Niggli: *op. cit.*, p. 312, 316, 434, 436.

[61] E. B. Bailey and C. W. Grabham: *op. cit.*, p. 253.

[62] N. L. Bowen: *Diabase and granophyre of the Gowganda Lake district, Quebec*, Jour. Geol., vol. 18 (1910) p. 658-674.

gabbros intruded into argillites. Water included in these sediments, Bowen believes, may have played a part in the transfer of the soda-rich solutions.

More recently, Bowen has favored an origin by replacement for all albite-rich rocks. He points out the absence of glassy rocks corresponding to granite rich in albite. Albitization is considered to be the "result of a secondary process of impregnation of solid rock with albite by circulating aqueous solutions. . . . There is nothing in the manner of their occurrence to warrant belief in their formation by the simple consolidation of a magma."[63]

Gillson has suggested that albitization may furnish the key to the origin of the alkaline rocks.[64] Gilluly has found evidence for believing that bodies of albite granite, many square miles in area, in eastern Oregon, have been formed by the hydrothermal alteration of hornblende-quartz diorite with which they are associated.[65]

SUMMARY OF EFFECTS IN NORTHERN INYO RANGE

The most significant phenomena discussed in this section may be summarized as follows:

(1) Alterations and replacements are confined almost exclusively to the Pellisier granite and to the meta-sediments in contact with it, and they are of the same type in each.

(2) The Boundary Peak granite appears to have been relatively little affected except by chloritization of biotite and the extensive replacement of potash feldspar by myrmekite. The outer margins are more sodic than are the deeper parts (p. 10 and Analyses 1 and 2).

(3) No constant increase in intensity of alteration is apparent as other intrusive rocks, lavas, or fault zones are approached. In general, the alterations are most extensive near large exposures of Boundary Peak granite. No part of the Pellisier mass is so far removed from an exposure of Boundary Peak granite as to rule out the latter as the source of the replacing solution.

(4) Various replacement textures can be differentiated and different stages in the replacement processes distinguished. By chemical analysis, a rough correlation can be established between a given texture and the degree of alteration that it represents. Although the governing conditions are so complex that it is not yet possible to arrive at valid generalizations, it seems probable that an orderly sequence of changes, applicable to each set of conditions, can ultimately be established.

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[63] N. L. Bowen: *Evolution of the igneous rocks* (1928) p. 132. Princeton.

[64] J. L. Gillson: *Origin of the alkaline rocks*, Jour. Geol., vol. 36 (1928) p. 471-474.

[65] James Gilluly: *Replacement origin of the albite granite near Sparta, Oregon*, U. S. Geol. Surv., Prof. Pap. 175-C (1933) p. 65-81.

(5) In the Boundary Peak granite contact aureole and in the Pellisier granite, a period of formation of potash feldspars appears to have preceded the introduction of albitizing solutions. In general, the contact rocks, which are at present exposed on the flanks of the batholith, exhibit marked development of potash feldspar metacrysts and of sericite-like mica. The formation of these apparently depended, at least in part, upon the introduction of material from the magma. The areas of most intense albitization, on the other hand, are within the Pellisier granite near the crest of the range or in the altered sediments, which, in places, lie above it. Here, in the granite, most of the potash feldspars are almost, or entirely, replaced by albite; within the sediments, large irregular-shaped bodies of rock, consisting almost exclusively of quartz and "chess-board" albite, are numerous. Some parts of the argillite appear to have been thoroughly saturated with sodic material, which converted virtually all the feldspars to albite.

(6) At least two types of albitization can be distinguished. No evidence has been found to indicate whether or not they were formed at different times. Probably, they belong to the same series of changes (p. 56).

(7) The changes described bear no relation to weathering nor to present permeability of the rocks. They are as far advanced in the bottoms of freshly glaciated cirques as in the most deeply weathered exposures.

(8) The introduction of soda was not invariably accompanied by a corresponding loss in potash. In some instances, the K_2O freed from the orthoclase remained in the rock, to be used up in the formation of sericite and other alteration minerals in the plagioclase feldspar or in the interstitial zones. The potash actually released from the rock may have been concentrated in the contact zones, forming potash feldspar metacrysts or sericite.

(9) Albitization and related alterations in the Pellisier granite are almost invariably associated with a peculiar texture, which, because of its resemblance to true cataclastic texture, has been called "pseudo-cataclastic texture."[66] Not only is it the dominant texture of the granite itself, but it is also common in the incompletely granitized sediments.

Pseudo-cataclastic texture may be briefly described as resembling mortar or mylonitic texture (according to its degree of development) in that it consists of larger xenomorphic grains of quartz and feldspar, set in a finer-grained matrix, which, at first glance, might appear to have been derived from these by crushing. It differs from true cataclastic textures, however, in that the grains of the groundmass are not fragments

[66] G. H. Anderson: *Pseudo-cataclastic texture of replacement origin in igneous rocks.* Am. Mineral., vol. 19, no. 5 (1934) p. 185-193.

of the larger grains, and also in that there is a strong suggestion of corrosion of the larger grains by the groundmass. Commonly, as will be discussed more fully later, where the groundmass borders potash feldspar, it is fringed with delicate myrmekitic intergrowths, and it contains several minerals, including much fine-grained albite, which are not represented among the larger grains, except as alteration products. Epidote, sericite, biotite, chlorite, magnetite, and secondary or recrystallized quartz make up the greater part of the groundmass.

As has been pointed out, rocks that have previously been subjected to mechanical deformation are especially likely to exhibit pseudo-cataclastic texture, because of the greater ease with which the necessary solutions can gain entrance to, and circulate in, them. Such rocks are also likely to be albitized, and for the same reason. But a preparatory crushing is by no means necessary for the development of either pseudo-cataclastic texture or albitization. Both are found where there is no other evidence of mechanical stress, such as bending or breaking of twinning lamellae of plagioclase grains, or even undulatory extinction in quartz. Neighboring rock masses, sedimentary and igneous, may be entirely free from any indications of stress. Dynamic metamorphism does not produce albitization or pseudo-cataclastic texture; it only facilitates their development.[67]

The groundmass of pseudo-cataclastic texture, in some instances at least, represents the residual portions of replaced (partly granitized) rock, the larger grains of plagioclase and potash feldspar being actually metacrysts, the growth of which appears to have involved both the recrystallization of minerals already present and the introduction of new materials from the magma. Later (or concurrent) reactions have produced an appearance suggestive of corrosion of metacrysts by groundmass.

Pseudo-cataclastic texture, whatever may have been its place in the development of Pellisier granite, is obviously chiefly of replacement origin. Where it has followed an earlier dynamic metamorphism the earlier effects have been, to a greater or less degree, obscured, and the present aspect is one of corrosion rather than of brecciation.

ALTERATION OF BOUNDARY PEAK GRANITE

The Boundary Peak granite is only as variable as might be expected in a granite formed by the ordinary process of crystallization from a magma, with some deuteric modifications. That significant changes in composition occurred is indicated by the microscopic evidence, a fact that tends to be substantiated by the analyses. Reference to analyses Nos. 1 and 2 will serve as an illustration. The former is of a sample taken

[67] *Op. cit.*, p. 191-192.

at an elevation of 9150 feet. The latter is of a specimen obtained almost directly above it, at an elevation of 11,200 feet. The difference in elevation probably indicates approximately the difference in depth within the batholith—i.e., Analysis No. 2 is of a rock about 2000 feet nearer the roof of the batholith than that of No. 1. Lime, magnesia, and soda increase; silica decreases; and alumina remains nearly constant, as the roof of the batholith is approached. The increase in the ratio of soda to potash is especially significant, for, if the Boundary Peak magma was the source of the solutions that albitized the Pellisier granite, marginal portions of the Boundary Peak granite might be expected to be (though not necessarily) affected, to a greater or less degree, by the same processes.

ALTERATION OF PELLISIER GRANITE

The study of albitization in the Pellisier granite and in the contact zones has given rise to the following general conclusions:

(1) The most intense effects have been produced in those parts of the granite close to the crest of the range and in the altered sediments that overlie the granite in this same region.

(2) In the contact zones along the flank of the batholith, magmatic emanations entering the altered sediments appear to have first formed potash feldspar metacrysts; some of these were partially albitized later.

(3) The albitizing solutions appear to have saturated the roof rocks, producing fine-grained secondary albite (comprising part of the groundmass in pseudo-cataclastic texture) and attacking and altering the feldspars.

(4) Albitization of the plagioclase feldspar appears to have been delayed until after the potash feldspars were completely albitized. When all the orthoclase and microcline had been replaced, however, the plagioclase was attacked, and, in some instances, it also was completely albitized. Where the potassic feldspars are strongly albitized, the neighboring plagioclase is commonly, though not invariably, altered to sericite or epidote. The potash liberated from the feldspars was probably partly, or wholly, used up in the formation of the sericite.

In some instances, however, comparatively little alteration of the plagioclase took place in the vicinity of highly albitized potash feldspar. The liberated potash appears to have been mostly, or completely, removed from the vicinity by the replacing solutions.

Where both potassic and plagioclase feldspars have been completely, or almost completely, albitized, neither the mica nor the epidote remains, and the quartz and the secondary albite, which make up most of the rock, appear entirely fresh and unaltered except for the chess-board structure of the albite and the highly sutured grain boundaries.

(5) Under the microscope, the Pellisier granite, in places, shows evidence of having been crushed. Possibly, the albitizing solutions may have gained access to the rock as a result of the increased permeability thus produced. Where cataclastic phenomena are noticeable, albitization is generally intense. On the other hand, albitization is equally intense in specimens that show no indications of having been subjected to dynamic metamorphism.

To summarize the results of the examination and the comparison of several hundred slides, the following changes took place when the albitic solutions invaded the rock:

(a) In some parts of the rock, the potassic feldspars only were albitized, and at least a large part of the replaced potash remained in the rock, to enter into the formation of sericite and possibly biotite in the plagioclase feldspar or in the interstitial zones. The lime liberated by the partial sericitization of the plagioclases, likewise, remained to form epidote. Some increase in iron may have accompanied these changes; the FeO—Fe_2O_3 content of different specimens of Pellisier granite is variable. The principal difference in chemical composition of the rock, however, as indicated by analyses, is in the increase of Na_2O and a corresponding increase in the total alkali content.

(b) In other parts, the potassic feldspars were albitized, but the plagioclase was not sericitized. The replaced potash was in large part lost from the rock. CaO, however, remained to form epidote and possibly other lime-containing minerals—e.g., titanite. The change in chemical composition was principally in an increase in soda and a loss of potash, the total alkali content remaining almost unchanged.

(c) In other exposures, the potassic feldspars were albitized, and also the plagioclase to some extent. The potash in part remained in the rock to form sericite as an alteration of the plagioclase, but CaO was lost; no epidote was formed. The principal change in composition was an increase in soda and in total alkali content, accompanied by decrease in lime.

(d) More rarely, both potassic and plagioclase feldspars were nearly completely albitized, but neither sericite nor epidote was formed, and even biotite underwent a marked reduction in amount. The chemical changes shown by analyses were a large increase in soda, a comparatively small increase in the proportion of silica, and a marked decrease of K_2O, CaO, and iron.

TYPES OF ALBITIZATION

In the Pellisier granite, two distinct types of albitization can be recognized. In one, the replacement effects are disseminated throughout the rock, with little apparent relation to major channel-ways. The type

of albitization to which they belong will, therefore, be termed the "disseminated type." In the other, the albitizing solutions evidently followed larger fractures or joints and produced intense alteration for distances—several inches; in some places, even feet—on both sides of the channelways. Beyond these relatively narrow zones, however, the host rock, presumably already modified by replacements, seems to have been little affected. This type is designated "the vein type."

To the field student, the vein type of albitization is much more apparent than is the disseminated type, for it is readily recognizable megascopically (Pl. 5, fig. 2). The effects produced by the disseminated type, on the contrary, are, in general, visible only under the microscope but are the more important. Nearly every grain of potash feldspar in the Pellisier granite is affected, at least to some degree. In many samples, the alteration has been so intense that the orthoclase and the microcline have been entirely converted into albite, and even primary plagioclase has been partly albitized. In some samples, the rock is composed of little except albite and quartz.

Although the two types have been discussed separately, probably they were part of the same series of changes and were formed at the same, or at nearly the same, time. That even the disseminated type is related, in some degree, to structure is suggested by the inequalities in intensity of alteration in different parts of the rock.

MICRO-STRUCTURES ASSOCIATED WITH REPLACEMENT

General statement.—The determination of the extent to which a rock has been affected by alterations of the disseminated type depends upon the recognition of various types of micro-structures within it. These are commonly associated with pseudo-cataclastic texture, but they may exist independently of it. Several of them are irregular or are so intricate that it is difficult to describe them or to represent them diagrammatically. To photograph them satisfactorily is often impossible, in part, because many of them exhibit little contrast, and, in part, because they can be observed or their significance made evident only as the stage of the microscope is rotated. In general, however, they can be classified into the following groups:

1. Myrmekites
2. Perthites
3. Mottled intergrowths
4. Sutured intergrowths
5. Granular intergrowths
6. Core-and-rim structures
7. Marginal corrosion structures
8. Chess-board structures
9. Intermediate and miscellaneous types

Of course, the various groups overlap to some extent, and it may be possible to assign some structures to more than one group.

Myrmekites.—Myrmekites, intergrowths of vermicular quartz and plagioclase feldspar, almost invariably involve replacement of orthoclase or microcline by sodic plagioclases. They were first described by Michel Levy,[68] sixty years ago. Three years later, Sederholm proposed the term "Myrmekite."[69] Many other petrographers have studied the structure and have attempted to account for its formation. M. Reinhardt[70] and Pentti Eskola[71] considered it to be an end-stage product in a crystallizing magma.

Others, observing the intergrowth in metamorphic rocks, have considered it to be a result of metamorphism. Tronquoy believed that it was due to what he called "auto-pneumatolysis," by which alkaline emanations or circulations proceeding from the unconsolidated part of a magma acted upon the minerals of the already consolidated part. He viewed it as a special kind of albitization.[72]

Becke at first regarded the structure as being due to simultaneous crystallization of its constituents from a magma. Later, he decided that myrmekite formation represents a replacement of the potassium in the potash feldspars, by the sodium and calcium of the plagioclase. As anorthite contains less silica than does orthoclase or microcline, the substitution of plagioclase for potash feldspar would liberate SiO_2 to form the quartz of the myrmekite. The more calcic the plagioclase of the myrmekite, the more silica would be set free. By careful measurements Becke thought that he obtained confirmation of these views.[73] He concluded that the reaction took place after the consolidation of all, or most, of the rock and was favored by the presence of aqueous solutions or vapor; hence, it is common in igneous rocks near the contact zones. He also suggested that the extensive formation of mica (both biotite and muscovite) in deep-seated rocks, after their consolidation, may in large part depend upon the potash set free by formation of myrmekite, and the giving off of potash in contact aureoles of plutonic rocks may be explained in the same way.

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[68] A. Michel Levy: *Structure microscopique des roches acides anciennes,* Bull. Soc. franç., minéral., t. 3 (1874) p. 201-222.

[69] J. J. Sederholm: *Über eine archaische Sedimentformation sudwestlichen Finlande,* Bull. Comm. géol. Finlande, no. 6 (1899) p. 108-114.

[70] M. Reinhardt: *Der Coziagneisszug in den Rumanischen Karpathen,* Inaug. Diss. Bucharest (1906) p. 78-79, 100.

[71] Pentti Eskola: *Petrology of the Orijarvi region,* Bull. Comm. géol. Finlande, no. 40 (1914) p. 27-28.

[72] M. R. Tronquoy: *Origine de la myrmekite,* Bull. Soc. franç., minéral., t .35 (1912) p. 214-223.

[73] F. Becke: *Über myrmekite,* Mitt. der Wiener Mineralog. Gesell., Tschermaks, Min. Petr. Mitt., vol. 27 (1908) p. 377-391; *Physiographie der Gemengteile der Krystallinen Schiefer,* Denkschr. Akad. Wiss., Bd. 75 (1913) p. 97-151, aber vorgelegt in der Sutzung volm 12 Juli (1906).

FIGURE 1. MYRMEKITES OF "WART-LIKE" FORM
Growing on border between plagioclase and potash feldspars, Boundary Peak granite. (Pl) plagioclase; (Or) orthoclase. Photomicrograph, crossed nicols, x 50.

FIGURE 2. MYRMEKITES FRINGING REPLACEMENT "VEIN"
Pseudo-cataclastic texture, which follows the boundary between two grains of potash feldspar (Or). Biotite, quartz, and albite compose the central part of the vein. The triangular-shaped light-colored grain projecting into the vein from the potash feldspar is quartz (Q). Photomicrograph, crossed nicols, x 50.

FIGURE 3. CLUSTERS OF MYRMEKITES REPLACING POTASH FELDSPAR (OR)
Photomicrograph, crossed nicols, x 50.

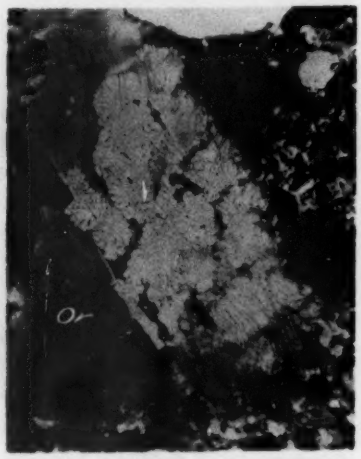

FIGURE 4. MYRMEKITE REPLACING POTASH FELDSPAR (OR) IN PSEUDO-CATACLASTIC GROUND MASS
As in Figures 2 and 3, no primary plagioclase is present in the section. Photomicrograph, crossed nicols, x 50.

TYPES OF MYRMEKITES

FIGURE 1. PATCH-AND-VEIN TYPE PERTHITE
The matrix, almost at extinction, is microcline; the patches are albite. Characteristic albite twinning is shown. Photomicrograph, crossed nicols, x 50.

FIGURE 2. IRREGULAR BORDERS OF ALBITE
Enlargement (about 2½ times) of Figure 1. Note blotchy appearance of the albite. Crossed nicols.

FIGURE 3. PATCH-AND-VEIN PERTHITE IN ROCK WITH PSEUDO-CATACLASTIC TEXTURE
Dark patches in the Carlsbad twin of orthoclase are albite. Photomicrograph, crossed nicols, x 50.

FIGURE 4. STREAKY PERTHITE
Dark matrix is orthoclase; the light streaks are albite. Photomicrograph, crossed nicols, x 50. (*See also* Plate 6, figure 1.)

PERTHITES

Becke's theory is the best substantiated and the most widely accepted explanation for the formation of myrmekite. In the Inyo batholith, myrmekite appears to have been formed invariably as an accompaniment of replacement of potash feldspar by plagioclase. In some instances, it was produced after a period of dynamic metamorphism, for it is common in Pellisier granite, in which the quartz is granulated, and the twinning lamellae in plagioclase feldspars are bent or broken. The structure is so delicate that it surely would not have escaped being crushed by granulation. The many examples, here and elsewhere in contact zones in partly recrystallized rocks, which, beyond question, never were molten, is conclusive proof that it is not invariably a product of magmatic crystallization.

In the Inyo batholith and associated rocks, two distinct types of myrmekites can be distinguished. The first, described by Sederholm [74] and other authors, is the wart-like form, which grows at the expense of potash feldspar where the latter is bordered by primary plagioclase. With this primary plagioclase, the plagioclase of the myrmekite generally appears to be continuous. This type is chiefly confined to the Boundary Peak granite, although it is found less commonly in the Pellisier granite and in some of the contact rocks (Pl. 7, fig. 1).

The second type forms lace-like fringes along the margins of veins or of groundmass associated with pseudo-cataclastic texture, where these cross or adjoin potash feldspars (Pl. 7, fig. 2). Fine-grained secondary albite is in many of the veins of the groundmass, but no primary plagioclase is visible. In many instances, the myrmekite is in grape-like clusters, apparently with no earlier plagioclase present (Pl. 7, fig. 3).

Myrmekites of the second type are common in the Pellisier granite and in the incompletely granitized rocks of the contact zone, but are not found in the Boundary Peak granite. They are particularly abundant in rocks exhibiting other replacement and alteration textures. Some of these rocks appear to have undergone severe crushing. As a structure so delicate probably could not survive dynamic metamorphism, the myrmekite must have been of later formation.

Perthites.—Perthites, as originally defined, are parallel intergrowths of orthoclase and albite, the orthoclase being the host.[75] The term as commonly used at present, however, includes irregularly shaped intergrowths of potash feldspar and plagioclase, many exhibiting slight

[74] J. J. Sederholm: *Synantectic minerals and related phenomena*, Bull. Comm. géol. Finlande, no. 48 (1916) p. 63-148.

[75] Thomas Thomson: *Notes of some new minerals*, Philos. Mag., vol. 22 (1843) p. 189.
Albert Johannsen: *Descriptive petrography of igneous rocks*, vol. 1 (1931) p. 223. Chicago.

parallelism. Where the plagioclase is the host, the intergrowth is termed "antiperthite." [76]

Although some of the common types of perthites may have originated [77] by exsolution, others have undoubtedly been formed by replacement.[78] In the perthites that have been examined from the Inyo batholith, albite replaces potash feldspar in all proportions. Three principal varieties can be recognized. These are the "patch and vein perthites," [79] the "streaky perthites," and the "injection perthites." [80]

Probably not all the perthites that are found in the Inyo batholith are of replacement origin. Other varieties are chiefly the "film" and the "rod" types, which are probably of exsolution origin.[81] The proportion that this exsolution albite bears to replacement albite, however, is small.

In the "patch and vein" perthites, irregularly shaped "patches" of albite, generally, though not invariably, connected by veins of various sizes, are distributed throughout the potash feldspar. The patches may be small or large; several may have coalesced; and, in many instances, the coalescence seems to have continued until little of the original potash feldspar grain remains. In the early stages, the replacements have usually been guided by the cleavage of the orthoclase, but, in the later stages, the orientation is lost (Pl. 8, figs. 1, 2, 3).

The albite is twinned in some of the patches and veins and untwinned in others. Its composition is about $Ab_{95}An_5$.

In the "streaky perthites," each grain of potash feldspar is crossed by veinlets of albite, in pattern that resembles the braided pattern shown by many streams of low gradient (Pl. 4, fig. 4; Pl. 8, fig. 4). The structure differs from the patch and vein type of structure, in the fineness of

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[76] J. J. Sederholm: *op. cit.*, p. 133.

Olaf Andersen: *Genesis of feldspar from granite pegmatites*, Norsk. geol. Tidsskr., Bd. 10, H. 1-2 (1928) p. 198-203.

[77] J. H. L. Vogt: *On the feldspar diagram*, Skr. norske Vidensk. Akad., I, Mat.-nat. Kl., no. L (1926).

H. L. Alling: *The potash-soda feldspars*, Jour. Geol., vol. 34 (1926) p. 591-611.

[78] Olaf Anderson: *op. cit.*, p. 166-171.

W. T. Schaller: *Replacement minerals in pegmatites*, Am. Mineral., vol. 12 (1926) p. 62. Schaller notes that, "In a recent paper by Alling, he is surprised that petrographers have often failed to recognize in perthites two distinct generations of the sodium feldspar, and I would add that I am surprised that petrographers have failed to recognize that the second type, which constitutes the great bulk of the perthites is a secondary replacement, for it is not difficult to find in many pegmatites examples where the microcline contains a varying quantity of the perthite lamellae, which reach a percentage of almost one hundred. In other words, the microcline has been practically completely perthitized."

See also J. L. Gillson: *The granite of Conway, New Hampshire, and its druse minerals*, Am. Mineral., vol. 12 (1927) p. 316.

[79] Olaf Andersen: *op. cit.*, p. 150-151.

[80] R. J. Colony: *Final consolidation phenomena in the crystallization of igneous rocks*, Jour. Geol., vol. 31 (1923) p. 169-178 (esp. Fig. 1, p. 171).

[81] C. H. Warren: *A quantitative study of certain perthitic feldspars*, Am. Acad. Arts Sci., Pr., vol. 51 (1915) p. 144.

Olaf Andersen: *op. cit.*, p. 116-205.

FIGURE 1. MOTTLED INTERGROWTH OF ORTHOCLASE AND ALBITE
Photomicrograph, crossed nicols, x 50.

FIGURE 2. PSEUDO-CATACLASTIC TEXTURE IN GRANITE
Grain of microcline (center) is being attacked from the margins by the groundmass and from within by myrmekitic intergrowths of albite and quartz. Clusters of myrmekite fringe the groundmass where it touches the microcline. Photomicrograph, crossed nicols, x 27.

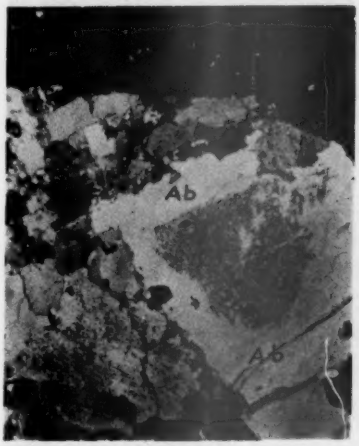

FIGURE 3. CORE-AND-RIM STRUCTURE
With core of orthoclase (Or) and rim of albite (Ab). Orthoclase is mottled with albite in the same optical orientation as the rim. Photomicrograph, crossed nicols, x 27.

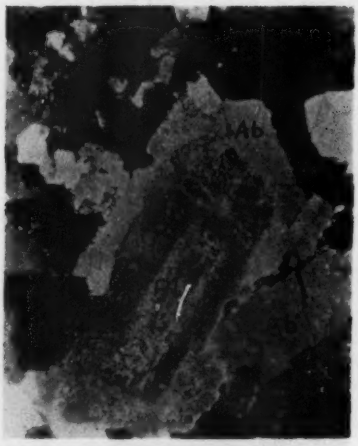

FIGURE 4. CORE-AND-RIM STRUCTURE
With core of plagioclase (Pl) and rim of albite (Ab). Plagioclase core is highly altered to fibrous white mica (sericite or paragonite); albite rim is mottled. Photomicrograph, crossed nicols, x 27.

REPLACEMENT TEXTURES

FIGURE 1. REPLACEMENT TEXTURE IN PELLISIER GRANITE
Large grain of chess-board albite (upper right) contains numerous small globules of quartz. Plagioclase grains (at extinction, left) contain flakes of sericite or paragonite. The light-colored grain (lower right) is albite. Photomicrograph, crossed nicols, x 50.

FIGURE 2. HIGHLY ALBITIZED PELLISIER GRANITE
Large mottled grains are intergrowths of albite in orthoclase. Several smaller grains of secondary quartz are shown. Photomicrograph, crossed nicols, x 50.

FIGURE 3. SUTURED INTERGROWTH OF MICROCLINE (M) AND ALBITE (Ab)
Photomicrograph, crossed nicols, x 50.

FIGURE 4. MICROCLINE ENCLOSED IN ALBITE
Unusual type of replacement texture. Microcline, readily recognizable by its twinning, is enclosed in albite (Ab) with an uneven extinction resembling undulatory extinction in strained quartz. The dark band crossing the field vertically is a break in the section. Photomicrograph, crossed nicols, x 27.

REPLACEMENT TEXTURES

the veins and in the absence of patches of noticeable size. The veinlets of albite, in some instances, apparently were guided by fractures formed in the potash feldspars in an earlier period of dynamic metamorphism. The albite in the veinlets is rarely twinned.

The "injection perthites" [82] are similar to the streaky perthites, except that the grains of orthoclase are surrounded by a rim of albite, stringers and veinlets from which appear to have penetrated between the cleavages of the orthoclase. The term is somewhat misleading, for the process was probably mostly replacement rather than forcible injection.

The replacement perthites are found almost exclusively in the Pellisier granite and in the associated contact rocks. Perthites of the "exsolution" type are common in the Boundary Peak granite, but those of replacement origin are rare.

Mottled intergrowths.—Mottled grains of orthoclase or microcline in the Pellisier granite are common (Pl. 9, fig. 1) when viewed between crossed nicols. This is especially characteristic of grains surrounded by rims of albite or of those sections in which most of the orthoclase has been albitized. Interference figures obtained from grains of this kind are invariably hazy and indistinct.

The mottling may be in part caused by the alteration of small blocks of albite and orthoclase, with contacts oblique to the plane of the section, so that the albite blocks are not sharply bordered but appear to grade into the neighboring blocks of orthoclase. More probably, however, most of the vague boundaries between albite and orthoclase are due to a gradational change in composition. Where no difference in refractive index can be detected between the adjoining blocks, they can be distinguished from each other only by differences in extinction and in optic sign. Such grains are partly but unevenly albitized.

Sutured intergrowths.—Albite is also found in orthoclase in irregular-shaped bodies with intricately sutured borders (Pl. 10, fig. 3). The albite is usually well twinned. These may be called sutured intergrowths.

Granular intergrowths.—Orthoclase or microcline may contain areas in which small grains of albite are thickly distributed. The areas are irregular in shape and size, and many of their borders are highly intricate (Fig. 10).

Somewhat similar granular intergrowths result from the alteration of plagioclase feldspar to epidote and sericite. Secondary minerals are distributed more evenly through the plagioclase grains; they are not concentrated in definite areas; and the grains are never interlocking, as the grains of albite in the potash feldspars commonly are.

[82] *Cf.* R. J. Colony: *op. cit.*, p. 173.

Core-and-rim structures.—Many of the earlier feldspars, both orthoclase and plagioclase, are surrounded by rims of albite. Structures of this kind have been referred to in the description of injection perthites (which are a special type of core-and-rim structure) and in the discussion of the mottled intergrowths. Where the cores are of orthoclase, they are usually partially albitized (Pl. 9, fig. 3). Most cores of plagioclase are strongly sericitized or epidotized, but some are relatively fresh (Pl. 9, fig. 4). Some of the rims are mottled but untwined; others have well-developed chess-board structure. The contact between core and rim may be fairly sharp or sutured or gradational.

FIGURE 10.—*Granular intergrowth of microcline and albite*

Small grains (center) are albite. Camera lucida drawing, x 25.

Marginal corrosion structures.—Many grains of potash feldspar (orthoclase or microcline), which lie in a pseudo-cataclastic groundmass, have the appearance of having been corroded along the margins. Different stages of this process may be recognized, ranging from those in which the initial boundaries of the grain are evident, to others in which the potash feldspar has been almost completely "digested" (Pl. 4, fig. 1). The groundmass ordinarily contains much fine-grained albite, and, where it borders the potash feldspars, it is almost invariably fringed with myrmekite. The central part of the potash feldspar commonly has an altered appearance, difficult to describe. Structures of this type are common throughout the Pellisier granite and the associated contact rocks, but, as in the case of most of the other structures described here, they are absent from the Boundary Peak granite.[83]

Chess-board structures.—Chess-board structures in albite were described by Becke in 1906.[84] He considered it to have originated by the complete replacement of orthoclase by albite; this is its probable origin in the

[83] *See also* G. H. Anderson: *Pseudo-cataclastic texture of replacement origin in igneous rocks*, Am. Mineral., vol. 19, no. 5 (1934) p. 190, fig. 2.

[84] F. Becke: *Physiographie der Gemengteile der Krystallinen Schiefer*, Denkschr. Kais. Acad. Wiss., Bd. 75 (1906) p. 124.

Pellisier granite. Here, it commonly forms rims about cores of potash or plagioclase feldspar, or is found as independent grains.

Chess-board albite is characterized by a blocky twinning structure, the twinning lamellae being short and broad and discontinuous, giving the grain an appearance somewhat resembling that of a chess-board (Pl. 4, fig. 3).

Albite with this structure has not been found in the Boundary Peak granite, but it is in the more strongly albitized parts of the Pellisier granite, in the albitite bodies above the roof of the batholith (p. 44), and in the albite "veins."

Intermediate and miscellaneous types.—Various replacement structures cannot accurately be referred to any of the foregoing groups. Some of these structures do not lend themselves readily to either description or illustration (Pl. 10, fig. 4). In this group may be placed grains of potash feldspar of an indefinable altered appearance ("sick-looking" is perhaps an appropriate term), which are common in the Pellisier granite. Most of them exhibit incomplete extinction and hazy and ill-defined interference figures. Microcline twinning, where present, is also vague and poorly defined, but is, nevertheless, recognizable. They are, perhaps, representative of incomplete stages in the pseudomorphic replacement of orthoclase by albite.

Pseudomorphs.—Grains that may be pseudomorphs of albite after microcline are occasionally found. They are distinguishable from potash feldspar by their index and optic sign. They do not exhibit albite twinning, but, where the replacement by albite is incomplete, vestiges of microcline twinning are preserved in some samples. In most instances, the microcline twinning is confined to a portion of the grain, the larger part being untwinned.

"VEIN" TYPE OF ALBITIZATION

In some exposures of granite near the summit of the range (as, for example, in the walls of the glacial cirques), albite veins form a veritable network, readily visible from considerable distance. The central parts of these veins are composed almost exclusively of "chess-board" albite, considered by Becke and others to be invariably of replacement origin.[85] In some places, quartz is relatively scarce; in others, it nearly equals the albite. All the constituents of the original rock appear to have been carried away by the invading solutions. As the margins of the veins are approached, increasing amounts of biotite are found, scattered through the albite; in many places, the proportion of quartz also increases. The

[85] *Ibid.*

transition to Pellisier granite, relatively unaltered except for changes produced in the earlier stages of replacement, is, in most instances, gradual, but is complete in distance commonly measurable in inches (Fig. 11).

Fractures filled with hematite are found in many of the veins. The

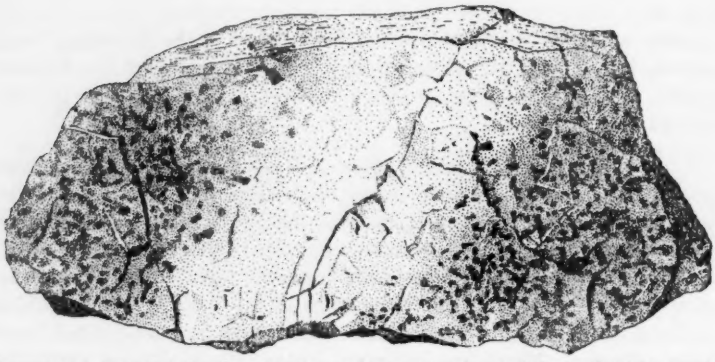

FIGURE 11.—*Detailed drawing showing replacement vein of albite in Pellisier granite*
Fractures in the middle of the albite vein are filled with hematite. About half natural size.

hematite was deposited at the close of the process. Some of the albite veins are bordered by manganese.

SECONDARY MICA

Abundantly distributed throughout most of the Pellisier granite, and present to much less extent in the Boundary Peak granite, is a fibrous white mica, which is mostly sericite, but which, in the more strongly albitized portions, may be the sodium mica, paragonite. These two micas are supposed to have similar optical properties.[86]

The sericite (or paragonite) is most abundant as an alteration product within the plagioclase feldspar; less commonly, it is present in considerable quantities in the potash feldspars. In pseudo-cataclastic texture, sericite is in the groundmass in elongated or sinuous fibers, but it is rare in the secondary albite, or in the albitized portions of the potash feldspar grains. In some altered schists in early stages of granitization in which orthoclase metacrysts have formed, sericite (or possibly bleached biotite) forms a large part of the groundmass.

In some deeply weathered rocks, and also in zones of hydrothermal alteration associated with recent faulting or with Tertiary or early

[86] N. H. Winchell and A. N. Winchell: *Optical mineralogy*, 2d ed., pt. 2 (1927) p. 364.
E. S. Larsen: *The microscopic determination of the non-opaque minerals*, U. S. Geol. Surv., Bull. 848 (1934) p. 167, 237.

Quaternary volcanic activity, a second period of alteration has sericitized all feldspars within the rocks, irrespective of origin. These effects are quite distinct from those already described, and undoubtedly belong to a different epoch in the petrologic history of the region.

In general, the more highly albitized the potassic feldspars are in a given rock, the more highly is the plagioclase altered to the sericite-like mica. The grains of plagioclase are commonly so largely converted to felted masses of fibrous mica that their original characters can be only vaguely discerned.

In some instances, the plagioclase has been altered to epidote or to a mixture of epidote and sericite. The most intensely albitized rocks, however, contain little or no sericite, epidote, or biotite. Both plagioclase and the potassic feldspars have been more or less completely converted to albite. The replacing albite itself is rarely altered.

EPIDOTIZATION

Although epidote is abundant as an alteration product of the plagioclase feldspar of the Pellisier granite, it is much less common than sericite in the Boundary Peak granite. In the contact zones, it is plentiful and widespread, but is rare in the potash feldspars and almost completely lacking in the secondary albite.

In some rocks, the formation of epidote appears to have accompanied the albitization of the potash feldspars. Although epidote and sericite may both be present as alteration minerals in the plagioclase, in places epidote is either alone or greatly exceeds the sericite. The correspondence between degrees of albitization and epidotization, though less pronounced than in a similar comparison involving sericite, is plainly not a matter of coincidence.

Where pseudo-cataclastic texture has been developed, the groundmass generally contains epidote in considerable abundance.

CLOUDING OF FELDSPARS

All types of feldspar in both granites and in the contact zone are more or less clouded by minute shreds and specks or rodlike particles of other minerals. In some specimens, these inclusions are finely divided kaolinite; in others, they are probably magnetite or hematite (p. 13; *see also* Analyses Nos. 14, 15, 16, 17). The particles are so small that identification is difficult. The cloudiness renders some feldspar grains almost opaque, to a decidedly less degree in the Boundary Peak granite than in the Pellisier granite or in the contact rocks.

The secondary albite is least clouded; most of it is almost, or quite, clear. Under the microscope, with plain light, it is generally possible to

recognize replacement albite within potash feldspar, by its freedom from inclusions.

The clouding of the feldspars forms two kinds of patterns. In one, the fine particles are more or less evenly distributed throughout the grain and are probably mostly hematite or magnetite; in the other, they are concentrated along cleavages or within certain twinning bands and are probably kaolinite. The first were probably formed during the period of contact metamorphism and granitization; the second is more probably the result of weathering and other later processes.

The clouding of feldspars as a result of contact metamorphism has been discussed by Teall,[87] Kynaston,[88] Bailey,[89] and, more recently, by MacGregor.[90]

The writer's conclusions are in agreement with those of MacGregor—namely, that clouding by iron oxides commonly accompanies contact metamorphism or metasomatism. MacGregor also observed, as has the writer, that soda-rich plagioclase is generally relatively little affected. "The least basic (outermost) parts of zoned crystals do not as a rule become clouded," he says,[91] "nor do those portions of the more basic interior that may have been replaced by albite feldspar before metamorphism." In the rocks that have been discussed in this paper, however, pronounced zoning in plagioclases is not commonly found except where an outer rim of albite has been formed by replacement (Pl. 9, figs. 3 and 4). Plagioclase is rarely albitized.

MacGregor [92] believes that the iron, present as inclusions, was originally dissolved in the feldspar, though he points out that it may have been concentrated to some extent by migration. In support of this hypothesis, he states the fact that "a certain amount of iron oxide is a fairly constant feature, but in the series oligoclase-anorthite the percentages are almost twice as great as most of the higher values recorded in albite or in potash-feldspars. It therefore seems possible that the preferential clouding of basic plagioclase is due to its having an original iron-content higher than that of albite or potassic feldspar."

In the rocks of the northern Inyo Range, the potassic feldspars are as strongly clouded as are the plagioclase feldspars, and only the albite is relatively clear. If the theory, that the Pellisier granite was formed by granitization of the sediments, is correct, it is reasonable to believe that

[87] Sir. J. J. R. Teall: *British petrography* (1888) p. 279-280. London.

[88] H. Kynaston: *Notes on contact metamorphism around the Cheviot granite*, Edinburgh Geol. Soc., Tr., vol. 8 (1905) p. 18, 20, 24.

[89] E. B. Bailey: *The geology of Ben Nevis and Glen Coe*, Geol. Surv. Scotland, Mem. (1916) p. 205, 208, 209.

[90] A. G. MacGregor: *Clouded feldspars and thermal metamorphism*, Mineral. Mag., vol. 22 (1931) p. 534-538.

[91] *Op. cit.*, p. 526.

[92] *Op. cit.*, p. 536.

the iron forming the inclusions in the feldspars was derived from sedimentary rocks, and that the albite is clear because it is of later origin, the solutions that deposited it having carried away the iron oxides.

CHEMICAL CHANGES RESULTING FROM ALBITIZATION

In the following analyses, the composition of relatively little-albitized Pellisier granite is compared with more highly albitized parts of the

TABLE 8.—*Chemical changes produced in the Pellisier granite by albitization*

(Ed Eisenhauer, Jr., Los Angeles, analyst; computations by R. P. Bryson, California Institute of Technology)

Constituents	Analyses			Recalculations of analyses on assumption that Al_2O_3 remains constant at value given in Analysis No. 5	
	(5) Comparatively little albitized Pellisier granite	(23) More strongly albitized Pellisier granite	(24) Albite vein in Pellisier granite	(23a)	(24a)
SiO_2	69.81	68.86	75.08	69.85	74.95
Al_2O_3	16.57	17.75	16.43	16.57	16.57
Fe_2O_3	1.45	0.64	0.18	0.65	0.18
FeO	3.00	1.54	0.96	1.56	0.96
MgO	0.46	0.28	0.09	0.28	0.09
CaO	2.80	1.07	0.89	1.09	0.89
Na_2O	2.70	4.59	4.53	4.66	4.52
K_2O	2.47	4.77	1.26	4.84	1.26
TiO_2	0.17				
Total	99.43	99.50	99.42	99.50	99.42

same rock. Unfortunately for the sake of precise estimates of gain or loss of material, it is not possible to separate changes due to albitization from those brought about by other alterations, nor to be sure that the initial composition of the granite from the different localities was the same.

Analysis No. 5 (Table 8) represents the composition of what, so far as can be determined by microscopic study, is a comparatively little-albitized specimen of Pellisier granite. (For the petrographic description of this rock, *see* p. 12).

Analysis No. 23 (Table 8) is of a more strongly albitized specimen from the main Pellisier granite mass at an elevation of about 9500 feet, just south of Middle Canyon, approximately at the contact with the Boundary Peak mass. A study of the thin section shows that the alterations are so extensive as to partly obscure the original mineral composition. The potash feldspars have been rather strongly albitized, and the associated plagioclase even more intensely sericitized. The texture is pseudo-cataclastic, with sericite, chlorite, quartz, bleached biotite, iron oxides, and albite composing the groundmass. The "primary" feldspars are strongly clouded, chiefly by kaolinite. Virtually no unbleached biotite remains in the rock.

Analysis No. 24 (Table 8) is of one of the albite veins within the Pellisier granite. The sample is composed almost entirely of quartz, feldspar, and a small amount of biotite. The feldspar is, in part, a mottled intergrowth of orthoclase and albite; the remainder is "chess-board" albite. The grain boundaries are highly sutured. The feldspars are somewhat clouded by finely divided non-opaque substances. Little sericite is present.

In the three rock analyses, the alumina content is nearly the same, and this constituent may have remained fairly constant. If this is actually the case, the highly albitized granite, 1554B, has been enriched in silica as well as in soda and has apparently suffered a loss of iron, lime, magnesia, and potash.

The points of greatest interest, of course, are the changes in total alkali content and in the soda-potash ratio. In analysis No. 23, the ratio has declined somewhat, as compared to No. 5, which microscopic examination has shown to be of a less strongly albitized rock than No. 24. The total alkali percentage in No. 23, however, has almost doubled, as compared with No. 5. The inference is that, in this instance, the potash liberated from the orthoclase has remained in the rock, where it has gone into the formation of other secondary minerals, probably mainly sericite. Accompanying the introduction of soda, there may have been actually some enrichment in potash from surrounding rocks. Microscopic evidence supports this conclusion, for, in rock represented in Analysis No. 24, the plagioclase feldspar is strongly sericitized, whereas in that represented in Analysis No. 5, though the albitization of orthoclase has been moderate, the sericitization of the plagioclase is relatively slight.

In Analysis No. 24, which is of a rock exhibiting strong albitization but little sericitization, the total alkali percentage is nearly the same as in Analysis No. 5, but the soda/potash ratio is more than three times as great. In this instance, nearly all of the replaced potash has been removed from the rock.

The apparent decrease in the content of CaO in Analysis No. 24, as compared with that of No. 5, is also significant, for it indicates that, where albitization accompanied by sericitization has taken place, lime may have been lost from the rock. In Analysis No. 24, the lower lime

content is a reflection of the complete albitization of the original plagioclase, as well as of the potash feldspars. The decrease in MgO in No. 23, however, is rather surprising in view of the rather high chlorite content.

COMPOSITION OF ALTERED FELDSPARS

Various samples of Boundary Peak granite and of Pellisier granite were crushed and screened, and, by repeated specific gravity separations, using bromoform and carbon tetrachloride mixtures in which pure albite would barely float, the grains were separated into two fractions. The lighter fraction contained the partly albitized potash feldspar grains, a little quartz, nearly all the biotite, more or less sericite, and considerable magnetite and hematite. Part of the iron oxide was removed by an electromagnet, but much of it was too finely disseminated in the feldspar to be removed.

In making the gravimetric separation, only the portion that passed through 60-mesh standard screen and failed to pass through 115-mesh was used in each case. The powder that passed through a 115-mesh standard screen was preserved but was not separated into light and heavy fractions.

After microscopic examination to test the completeness of the separation, the powders were chemically analyzed. The results of the analyses follow.

Analysis No. 25 (Table 9) represents the composition of the light fraction composed almost entirely of the potassic feldspars from a specimen of typical Boundary Peak granite. The composition of the entire rock is given in Analysis No. 1. Analysis No. 26 (Table 9) similarly, gives the composition of the light fraction composed almost exclusively of the potassic feldspars from another specimen of Boundary Peak granite, from a point approximately 2,000 feet nearer the roof of the batholith. The analysis of the entire rock is given in Analysis No. 2. Both rocks show relatively little albitization of potassic feldspars and comparatively slight alteration of the plagioclase feldspars, but the albitization is more pronounced in the rock of Analysis No. 26, which is nearer the upper margin of the batholith, than in that of Analysis No. 25.

Analysis No. 27 (Table 9) is of the fraction composed almost entirely of partly albitized potash feldspars from a specimen of Pellisier granite, obtained from a point near the bottom of a Tioga-stage glacial cirque, at an elevation of 10,000 feet, north Chiatovich Canyon. This granite contains, besides the altered potash feldspar, quartz, a rather small amount of plagioclase of composition about $Ab_{88}An_{12}$, biotite, chlorite, and magnetite or hematite. The orthoclase is moderately albitized, but some grains are almost unaltered. The oligoclase is not strongly sericitized, but it contains some epidote; epidote is also found in the pseudo-cataclastic groundmass. Most of the grains of potash feldspar are strongly clouded by finely divided minerals, probably chiefly hematite, kaolinite, and epidote.

Analysis No. 28 (Table 9) is of a specimen of the partly altered potash feldspars from the Pellisier granite, from the crest of the range west of Indian Canyon, at an elevation of 12,600 feet. The rock is a coarse-grained gneissic granite with a high

TABLE 9.—*Alteration of feldspars*

(Ed Eisenhauer, Jr., Los Angeles, analyst)

	Analyses of partly albitized Pellisier granite				Analyses of feldspars				
	Composition of granite	Composition of light and heavy fractions			Comparatively little-altered potash feldspars				Strongly albitized feldspars
	(29) Partly albitized Pellisier granite	(30) Fraction composed chiefly of moderately albitized potash feldspar grains	(31) Fraction containing most of the quarts, plagioclase, biotite, epidote, calcite, sericite, and opaque minerals	(32) Fine powder remaining after removal of coarse grains analysed in Nos. 30 and 31	(25) From typical Boundary Peak granite	(26) From Boundary Peak granite about 2000 feet nearer the roof of the batholith	(27) From unweathered Pellisier granite exposed in fresh glacial cirque	(28) From weathered Pellisier granite exposed on crest of range	(33) From nearly completely granitized sediment from Upper Indian Canyon
SiO_2	71.20	64.11	81.42	*	62.22	62.60	62.95	63.40	70.60
Al_2O_3	16.08	22.39	7.96	*	23.45	23.21	23.02	22.69	17.90
Fe_2O_3	1.39								2.19
FeO	1.74								
MgO	tr.								0.11
CaO	2.86								1.62
Na_2O	3.00	3.48	2.78	3.12	1.84	2.22	2.70	2.43	6.05
K_2O	3.44	5.06	1.27	3.43	6.70	6.31	5.85	5.56	1.08
TiO_2	0.06								
Total	99.77	95.04	93.43	6.55					99.55*
Na_2O/K_2O ratio	0.87	0.69	2.19	0.91	0.27	0.35	0.46	0.44	5.6
Total alkalies	6.44	8.54	4.05	6.55	8.54	8.53	8.55	7.99	7.12
Orthoclase	20.3	29.9	7.5	20.2					6.33
Albite	25.4	29.4	23.5	26.4					51.27
Ratio Ab/Or	1.25	0.98	3.13	1.31	15.5/39.6 (=0.39)	18.8/37.3 (=0.50)	22.8/34.6 (=0.66)	20.5/32.9 (=0.62)	8.09

* Partial analysis.

mafic content, forming part of the main igneous mass. It contains potash feldspar, quartz, oligoclase, and biotite, the last in large flakes, partly chloritized. Potash feldspar, which exceeds plagioclase, is, contrary to the general rule for the crest of the range, only moderately albitized.

All are partial analyses. Only the values for silica, alumina, iron, soda, and potash are given.

These data agree closely with the estimates of degree of albitization, formed from microscopic observations, the soda/potash ratio increasing in about the same proportion as the observed increase in albitization. However, the increase in the ratio in the separated potash feldspars (0.27 to 0.35) is not as great as in the corresponding entire rocks, Analyses Nos. 9 and 1 (0.71 to 1.14). The difference is probably chiefly due to the increased proportion of myrmekite in rock of Analysis No. 2, most of which, because of the intimate intermixture with quartz, would be included in the heavier fraction.

Analysis No. 29 (Table 9) is of a facies of Pellisier granite with potash feldspars more strongly albitized than in any of the preceding examples. Streaky perthites, mottled intergrowths of orthoclase and albite, and incompletely developed chessboard albite are present. The accompanying plagioclase is also strongly sericitized, although it is not as much altered as in sample of Analysis No. 23. The total plagioclase content is exceptionally low—not more than 20 percent of the rock—and much of it is sericitized. The rock also contains quartz, partly bleached biotite, and sericite, magnetite, epidote, zoisite, titanite, a small amount of chlorite, and a little free calcite. The texture is moderate pseudo-cataclastic, with much sericite, quartz, bleached biotite, calcite, and magnetite in vein-like interstitial material. The feldspars are moderately clouded. Considerable apatite is present.

Analysis No. 30 (Table 9) gives only the percentages of silica, alumina, soda, and potash of a sample composed chiefly of the partially albitized potash feldspar grains from the same rock as No. 29.

Analysis No. 31 (Table 9) gives the percentages of the same units of a sample containing most of the quartz, altered plagioclase, biotite, epidote, calcite, titanite, "leucoxene", sericite, and opaque minerals from the same rock as Nos. 29 and 30. Both 15 and 16 were of grains of standard screen fraction (-60-115).

Analysis No. 32 (Table 9) gives only the percentages of soda and potash from the crushed rock, which passed through the 115-mesh screen. No attempt was made to separate it.

If all of the K_2O is computed as representing orthoclase or as derived from it, and all the Na_2O as representing albite or derived from it (an assumption possibly fairly well justified, at least for Analysis No. 30), the mineral composition should be as calculated.

If these relations are approximately correct for Analysis No. 30, the orthoclase grains of the rock are, as an average, half-albitized, a conclusion which agrees well with previously formed estimates from microscopic observations.

* Partial analysis.

Analysis No. 33 (Table 9) is of the albitized feldspars from a nearly completely granitized sediment from Upper Indian Canyon. In addition to the strongly albitized feldspars, the rock contains a moderate amount of quartz, considerable partially bleached biotite, and a small amount of chlorite.

Fibrous white mica (sericite) is present in the feldspars, but is not abundant. Some of the plagioclase contains numerous small globules, or droplets, of quartz. The predominant texture is pseudo-cataclastic. The analyzed sample (screen size -60-115 mesh) contains small grains of magnetite, a little chlorite, and a small amount of quartz included within the feldspar grains.

SOURCE OF THE SOLUTIONS

The Boundary Peak magma is believed not only to have been the agent responsible for the formation of the Pellisier granite but also to have been the source of the soda-rich solutions which later affected it. As already pointed out, albitization of the potash feldspars has taken place, both in the Pellisier granite itself and in the incompletely granitized sediments, in many parts of the contact zone. The most intense alterations are in those parts of the Pellisier granite that are near to, or overlie, exposures of the Boundary Peak granite.

The process by which highly sodic liquids may be concentrated near the close of the period of magmatic crystallization is too well known to require discussion.[93]

Unquestionably, a large magma would be required to furnish sufficient soda to produce the wholesale albitization that has been observed in the northern Inyo region. The Boundary Peak granite is a large body. The surface exposures are extensive; the subjacent portions are doubtless much larger. They probably underlie, at no great depth, all the rocks exposed in the northern Inyo Range, and probably, also, those extending far to the south. Of the two granites, the Boundary Peak is surely much larger—that is, whereas the Pellisier granite has a maximum thickness of 2000 or 3000 feet, the Boundary Peak granite may be many thousands of feet, or even miles, thick.

The feldspars of the Boundary Peak granite are, with few exceptions, only slightly albitized. Chlorite is abundant, however, and epidote is present in some parts of the rock. Moreover, the marginal portions are decidedly more sodic than are those of the interior (*See* Analysis Nos. 25-28).

This increase in soda appears to be accompanied by a corresponding increase in abundance of the two varieties of myrmekite described in this paper (p. 59).

[93] N. L. Bowen: *The evolution of the igneous rocks* (1928) p. 34. Princeton.
James Gilluly: *Replacement origin of albite granite near Sparta, Oregon*, U. S. Geol. Surv., Prof. Pap. 175-C (1933) p. 77.

Even if the marginal parts of the Boundary Peak granite showed no albitization whatever, that condition would be no proof that the solutions came from some other source. Evidently, whether or not the potash feldspars and the earlier plagioclase were replaced by albite, depended upon existing conditions of temperature, pressure, and concentration of solutions, and possibly also upon the presence or absence of other materials. When the albitizing solutions were liberated from the interior of the Boundary Peak granite, the outer parts of that body were doubtless still much hotter than the intruded country rocks, and entirely different effects might, therefore, be expected in the one as compared to the other. In this connection, it should be remembered that pegmatites, in passing from the parent igneous mass into the surrounding rocks, in many instances, change abruptly in both composition and texture.

An alternative hypothesis is that the granitizing and albitizing solutions were furnished by an older intrusive, which was completely engulfed and assimilated by the Boundary Peak granite. This hypothesis can be neither proved nor disproved by the evidence available. It is abandoned in favor of the simpler and more probable theory that the solutions were derived from the Boundary Peak magma.

Partial albitization of the potash feldspar metacrysts in the incompletely granitized sediments of the contact zones is evidence that the alterations did not precede the intrusion of the Boundary Peak. If, on the other hand, the source of the albitic solutions were a subjacent magma of later emplacement, it is to be expected that the Boundary Peak granite would be as strongly, or more strongly, albitized than are those portions of the Pellisier that lie above it. This is not the case.

CONCLUSIONS

From his study of the Inyo batholith, the writer believes that the Pellisier granite was formed *in situ*, by the granitization of a series of early Cambrian or pre-Cambrian sediments and interbedded volcanic rocks. The evidence indicates that the Boundary Peak granite was the source of the emanations that took part in the conversion of the sediments into granite. No field or microscopic observations have been made that would suggest that the Boundary Peak granite was formed in any other way than by crystallization from a magma.

Heat and pressure, as well as addition of material, were important in the process of granitization. A comparison of the chemical composition of relatively little-altered sediments with that of typical Pellisier granite indicates that, in some instances, little change in composition was

necessary to cause the transformation.[94] In most instances, however, it is clear that definite chemical changes have taken place.

Initial differences in composition and texture of the sediments, in composition and concentration of magmatic materials, and in conditions of temperature and pressure have produced corresponding differences in texture and composition of the Pellisier granite. In contrast with the latter, the Boundary Peak granite is fairly uniform in both composition and texture.

During granitization, probably at a late stage of the process, the Pellisier granite and its associated contact rocks were extensively albitized. The potash feldspars were most affected, but, in places, the plagioclase feldspar was also involved. In some places, the changes were so thorough that rocks were formed that consist, almost exclusively, of chess-board albite and quartz. Enrichment in soda was, in many instances, accompanied by a corresponding loss of potash and, possibly, also of lime from the rock. In as many instances, however, these substances remained to form sericite and epidote, and the total alkali content was increased as soda was introduced.

The albitization of the feldspars of the Pellisier granite and the accompanying chemical and mineralogical changes, which have been discussed in this paper, are doubtless to be considered as different stages in the same series of processes by which the Pellisier granite was formed. They are closely related, also, to the post-consolidation changes that have affected the Boundary Peak granite. The liquids, gases, and other agents, which were effective, undoubtedly had a common source; that is, they were derived from the Boundary Peak magma, at different periods of its emplacement and crystallization.

[94] E. S. Bastin: *Chemical composition as a criterion in identifying metamorphosed sediments*, Jour. Geol., vol. 17 (1909) p. 446. "Certain clay schists can unquestionably possess the composition of granites."

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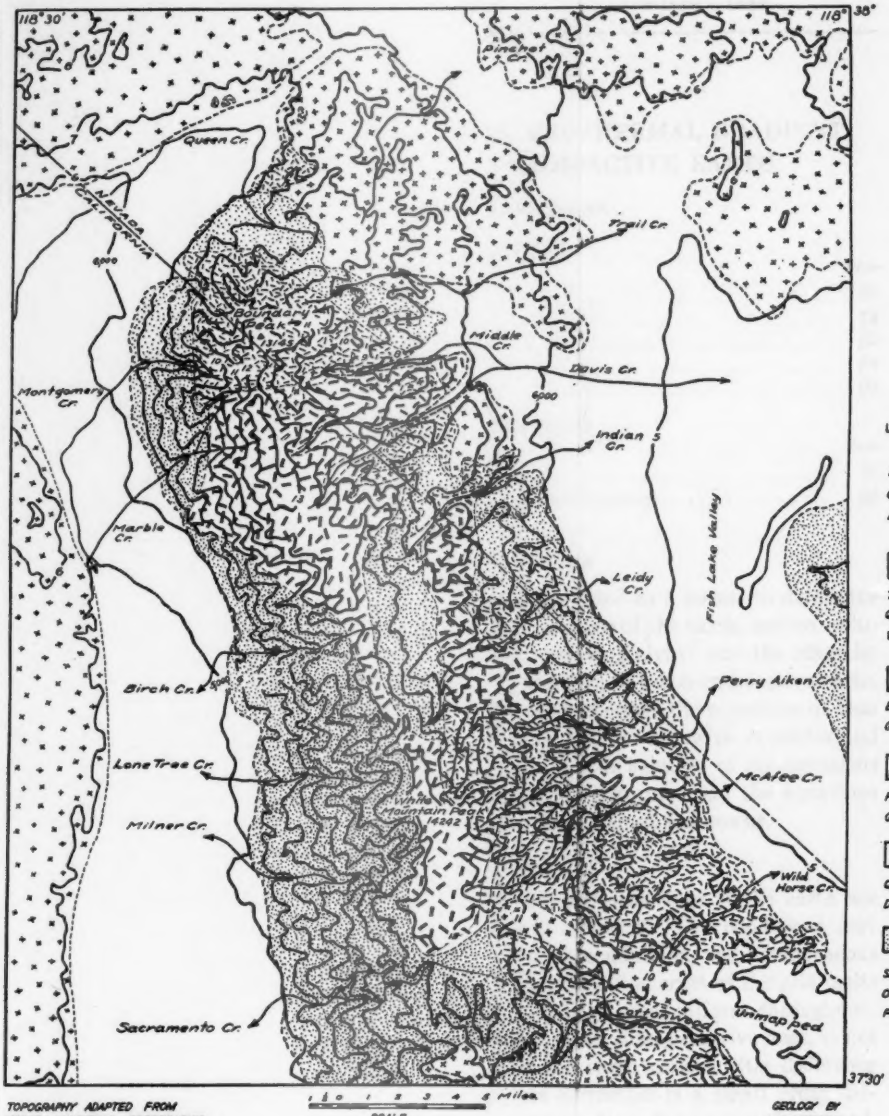

TOPOGRAPHY ADAPTED FROM WHITE MOUNTAIN TOPOGRAPHIC SHEET, U.S. GEOLOGICAL SURVEY
ONLY 1000 FOOT CONTOUR INTERVALS ARE SHOWN
DATUM IS MEAN SEA LEVEL

GEOLOGY BY G.H. ANDERSON

GENERALIZED GEOLOGICAL MAP OF WHITE MOUNTAIN QUADRANGLE

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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TABLES OF TEMPERATURE, GEOTHERMAL GRADIENT, AND AGE OF A NON-RADIOACTIVE EARTH

BY H. CECIL SPICER

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INTRODUCTION

Among the methods that have been presented as a means to determine the age, temperature gradient, and temperature of the earth, are two solutions based on the linear flow of heat, one by Kelvin [1] and the other by Ingersoll and Zobel,[2] both solutions pertaining to a non-radioactive earth. As it is somewhat difficult to visualize and interpret the equations of heat flow, an evaluation of the two solutions is given herewith in tables and figures. The range of constants chosen for the solution of the equations is ample to cover those mentioned in the literature, and the equations have been transformed and solved for the different unknowns.

KELVIN SOLUTION

Certain simplifying conditions for the physical state of the earth are assumed in order to obtain the Kelvin solution. The conditions are: (a) that the earth is a hot body, cooling by conduction, and homogeneous throughout; (b) that, initially, it had a crystalline crust of definite melting point; (c) that the temperature, initially, was uniform throughout; (d) that the effect of all sources of heat, other than primitive heat, is not considered; (e) that the curvature of the earth makes little difference (Woodward [3] has since shown that this correction is a small order difference); (f) that the diffusivity is constant from the surface downward.

[1] Lord Kelvin: *On the secular cooling of the earth*, Royal Soc. Edinburgh, Tr. vol. 23 (1862) p. 157-169.
[2] L. R. Ingersoll and O. J. Zobel: *Mathematical theory of heat conduction* (1913) p. 88-90.
[3] R. S. Woodward: *Annals of Mathematics*, vol. 3 (1887) p. 75-78.

The equation derived from the above assumptions is,

$$v = v_o \cdot \frac{2}{\sqrt{\pi}} \int_0^{\beta} e^{-\beta^2} d\beta, \beta = \frac{x}{2\sqrt{\kappa t}} \qquad \ldots (1)$$

in which

v = temperature, Centigrade, at any depth
v_o = initial temperature, Centigrade
x = depth in centimeters
t = time in seconds
κ = diffusivity in C.G.S. units

Equation (1) satisfies the conditions $v = 0$ at $x = 0$ for all values of t, and $v = v_o$ for all values of x when $t = 0$. Equation (1) is the solution for a semi-infinite solid, which extends, relative to the coordinate axes, in all directions to infinity except in the negative x-direction; and the yz-plane is the bounding face. In this way, surface boundary conditions need not be considered, except for the yz-plane through the origin. This may be likened to a slab, which extends to infinity in length and is encased on all sides by a perfect insulator, so that with one end heated and the other at 0° C, heat flows only in one direction.

Figure 1, which is plotted from Table 1, column 5, shows the depth-temperature curves of the Kelvin solution, for different times. *AB* represents the initial constant temperature throughout the mass, which is here assumed to be, $v_o = 3871°$ C. $= 7000°$ F. Beginning with the time $t = 0$, the yz-plane is assumed to remain at a constant temperature 0°C; and all the heat brought to the surface plane by conduction is carried away by melting ice, or some other means, as soon as it reaches *OA*, the surface plane. At a time t, the temperature may be read for any depth x, as the curves represent the temperatures in the planes perpendicular to the depth axis.

The derivative of equation (1),

$$\frac{\partial v}{\partial x} = \frac{v_o}{\sqrt{\pi \kappa t}} e^{-\frac{x^2}{4\kappa t}} \qquad \ldots . (2)$$

gives the geothermal gradient; values of the reciprocal geothermal gradient for the Kelvin solution are tabulated in Table 1, columns 3 and 4, at depths and times corresponding to those of equation (1). A dif-

fusivity of 0.0064, the average value for crustal rocks as given by Ingersoll and Zobel, was used in the solution of equations (1) and (2).

Solving equation (2) for t when $x = o$,

$$t = \frac{v_o^2}{\pi\kappa\left(\frac{\partial v}{\partial x}\right)^2} \qquad \ldots . (3)$$

gives the age, assuming $\frac{\partial v}{\partial x}$ to be the surface geothermal gradient. Equation (3), which gives the age of the earth in the Kelvin solution,

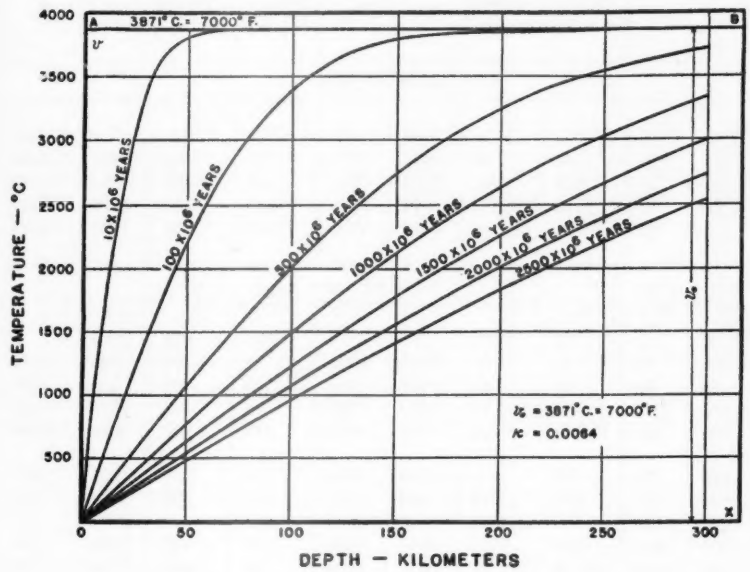

FIGURE 1.—*Depth-temperature curve (Kelvin solution)*

is evaluated in Table 2. The range of assumed constants is: $\kappa = 0.0016$ to 0.0196; $v_o = 3871°$ C. $= 7000°$ F. in the upper part of the table, and $v_o = 1936°$ C. $= 3516°$ F. in the lower; $\frac{\partial v}{\partial x} = 1°$ F. per 50 feet to 1° F. per 200 feet. Thus, the age, from Table 2, for a non-radioactive earth with an initial temperature of 7000° F. and a diffusivity of $\sqrt{\kappa} = 0.08$, is 178×10^6 years, if the geothermal gradient is assumed to be 1° F. per 50 feet; 711×10^6 years for a gradient of 1° F. per 100 feet.

TABLE 1.—*Temperatures and gradients in a non-radioactive earth*

Depth		Kelvin				Ingersoll-Zobel			
		$\kappa = 0.0064$ $v_0 = 3871°$ C. $= 7000°$ F.				$\kappa = 0.0064$ $m = 4°$ C. per km. $v_s = 1400°$ C. $= 2552°$ F.			
		Recip. Gradient		Temperature		Recip. Gradient		Temperature	
Km.	Mi.	Meters per °C.	Feet per °F.	°C.	°F.	Meters per °C.	Feet per °F.	°C.	°F.
				10×10^6 years					
0	0	6	12	0	0	17	31	0	0
25	16	14	26	3044	5511	34	62	1201	2194
50	31	144	262	3821	6910	153	280	1582	2880
75	47	7143	13,019	3870	6998	247	450	1700	3092
100	62	$\rightarrow \infty$	$\rightarrow \infty$	3871	7000	250	456	1800	3272
				100×10^6 years					
0	0	21	38	0	0	46	84	0	0
25	16	22	40	1184	2163	49	90	528	982
50	31	28	51	2201	3994	59	108	996	1825
75	47	41	75	2950	5342	78	143	1367	2493
100	62	71	129	3424	6195	110	200	1638	2980
125	78	142	260	3681	6658	153	279	1831	3328
150	93	334	610	3800	6872	197	359	1974	3585
175	109	901	1642	3848	6958	227	414	2092	3798
200	124	3030	5523	3865	6989	243	442	2198	3988
225	140	$\rightarrow \infty$	$\rightarrow \infty$	3870	6998	248	452	2299	4170
250	155			3871	7000	249	455	2400	4352
275	171			3871	7000	250	455	2500	4532
300	186			3871	7000	250	456	2600	4712
				500×10^6 years					
0	0	46	84	0	0	84	154	0	0
25	16	47	85	541	1006	85	155	295	563
50	31	49	89	1065	1949	88	160	585	1085
75	47	53	96	1557	2835	92	168	863	1585
100	62	59	107	2007	3645	99	180	1126	2059

TABLE 1.—*Temperatures and gradients in a non-radioactive earth*—continued

Depth		Kelvin				Ingersoll-Zobel			
		$\kappa = 0.0064$ $v_o = 3871°$ C. $= 7000°$ F.				$\kappa = 0.0064$ $m = 4°$ C. per km. $v_s = 1400°$ C. $= 2552°$ F.			
		Recip. Gradient		Temperature		Recip. Gradient		Temperature	
Km.	Mi.	Meters per °C.	Feet per °F.	°C.	°F.	Meters per °C.	Feet per °F.	°C.	°F.
500×10^6 years—continued									
125	78	68	124	2404	4359	107	195	1369	2496
150	93	80	146	2744	4971	118	214	1592	2898
175	109	98	179	3026	5479	130	237	1795	3263
200	124	124	226	3254	5889	144	263	1977	3591
225	140	161	294	3432	6210	160	292	2141	3886
250	155	216	394	3567	6453	176	322	2290	4154
275	171	299	546	3666	6631	192	350	2426	4399
300	186	427	779	3736	6757	206	376	2551	4624
400	249	2439	4446	3852	6966	241	439	2993	5419
500	311	$\rightarrow \infty$	$\rightarrow \infty$	3869	6996	249	453	3399	6150
600	373			3871	7000	250	456	3800	6872
700	435			3871	7000	250	456	4200	7592
1000×10^6 years									
0	0	65	119	0	0	105	191	0	0
25	16	66	120	383	721	105	192	239	462
50	31	67	122	761	1402	106	194	475	887
75	47	70	127	1126	2059	109	198	707	1305
100	62	74	134	1476	2689	112	204	934	1713
125	78	79	144	1804	3279	116	212	1152	2106
150	93	86	157	2108	3826	122	222	1362	2484
175	109	95	173	2385	4325	128	234	1563	2845
200	124	107	194	2634	4773	135	247	1752	3186
225	140	122	222	2853	5167	144	262	1932	3510
250	155	141	257	3044	5511	152	278	2101	3814
275	171	166	302	3208	5806	162	295	2260	4100
300	186	198	362	3346	6055	172	313	2410	4370
400	249	472	860	3691	6676	210	382	2935	5315
500	311	1429	2604	3821	6910	235	429	3382	6120

TABLE 1.—*Temperatures and gradients in a non-radioactive earth*—continued

Depth		Kelvin				Ingersoll-Zobel			
		$\kappa = 0.0064$ $v_o = 3871°$ C. $= 7000°$ F.				$\kappa = 0.0064$ $m = 4°$ C. per km. $v_s = 1400°$ C. $= 2552°$ F.			
		Recip. Gradient		Temperature		Recip. Gradient		Temperature	
Km.	Mi.	Meters per °C.	Feet per °F.	°C.	°F.	Meters per °C.	Feet per °F.	°C.	°F.
				1000×10^6 years—continued					
600	373	∞	∞	3860	6980	246	448	3796	6865
700	435			3869	6996	249	454	4199	7590
800	497			3871	7000	250	455	4600	8312
900	559			3871	7000	250	456	5000	9032
				1500×10^6 years					
0	0	80	145	0	0	117	213	0	0
25	16	80	146	313	595	117	214	213	415
50	31	81	148	623	1153	118	216	425	797
75	47	84	152	927	1701	120	219	635	1175
100	62	87	158	1221	2230	122	223	842	1548
125	78	91	165	1504	2739	125	228	1044	1911
150	93	96	175	1772	3222	129	235	1241	2266
175	109	103	187	2024	3675	133	242	1432	2610
200	124	111	202	2259	4098	138	251	1617	2943
225	140	121	221	2475	4487	143	261	1795	3263
250	155	134	243	2672	4842	149	272	1966	3571
275	171	149	271	2850	5162	156	283	2131	3868
300	186	168	305	3008	5446	162	296	2288	4150
400	249	298	544	3468	6274	192	350	2854	5169
500	311	625	1139	3708	6706	218	398	3341	6046
600	373	1562	2848	3814	6897	236	431	3779	6834
700	435	4546	8285	3854	6969	245	447	4194	7581
800	497	∞	∞	3867	6993	249	453	4598	8308
900	559			3870	6998	250	455	5000	9032
1000	621			3871	7000	250	456	5400	9752
1100	684			3871	7000	250	456	5800	10472

TABLE 1.—*Temperatures and gradients in a non-radioactive earth*—continued

Depth		Kelvin				Ingersoll-Zobel			
		$\kappa = 0.0064$ $v_o = 3871°$ C. $= 7000°$ F.				$\kappa = 0.0064$ $m = 4°$ C. per km. $v_s = 1400°$ C. $= 2552°$ F.			
		Recip. Gradient		Temperature		Recip. Gradient		Temperature	
Km.	Mi.	Meters per °C.	Feet per °F.	°C.	°F.	Meters per °C.	Feet per °F.	°C.	°F.
				2000×10^6 years					
0	0	92	168	0	0	126	230	0	0
25	16	92	168	271	520	126	230	198	388
50	31	94	170	541	1006	127	232	395	743
75	47	95	174	806	1483	128	234	591	1096
100	62	98	178	1065	1949	130	237	785	1445
125	78	101	185	1316	2401	132	241	976	1789
150	93	106	193	1557	2835	135	246	1163	2125
175	109	111	203	1788	3250	138	251	1347	2457
200	124	118	215	2007	3645	142	258	1526	2779
225	140	126	230	2212	4014	146	265	1700	3092
250	155	136	247	2404	4359	150	273	1869	3396
275	171	147	268	2581	4678	155	282	2033	3691
300	186	160	292	2744	4971	160	291	2192	3978
400	249	248	451	3254	5889	183	334	2777	5031
500	311	433	789	3567	6453	207	377	3290	5954
600	373	855	1558	3737	6759	226	412	3751	6784
700	435	1923	3505	3818	6904	239	435	4181	7558
800	497	4762	8679	3852	6966	245	447	4593	8299
900	559	$\rightarrow \infty$	$\rightarrow \infty$	3865	6989	248	453	4998	9028
1000	621			3869	6996	250	455	5399	9750
1100	684			3871	7000	250	456	5800	10472
1200	746			3871	7000	250	456	6200	11192
1300	808			3871	7000	250	456	6600	11912
1400	870			3871	7000	250	456	7000	12632
				2500×10^6 years					
0	0	103	188	0	0	133	243	0	0
25	16	103	188	243	469	133	243	188	370

TABLE 1.—*Temperatures and gradients in a non-radioactive earth*—continued

Depth		Kelvin				Ingersoll-Zobel			
		$\kappa = 0.0064$ $v_o = 3871°$ C. $= 7000°$ F.				$\kappa = 0.0064$ $m = 4°$ C. per km. $v_s = 1400°$ C. $= 2552°$ F.			
		Recip. Gradient		Temperature		Recip. Gradient		Temperature	
Km.	Mi.	Meters per °C.	Feet per °F.	°C.	°F.	Meters per °C.	Feet per °F.	°C.	°F.
		2500×10^6 years—continued							
50	31	104	190	484	903	134	244	375	707
75	47	106	193	722	1332	135	246	561	1042
100	62	108	197	956	1753	136	248	746	1375
125	78	111	203	1184	2163	138	251	928	1702
150	93	115	210	1406	2563	140	255	1108	2026
175	109	120	218	1619	2946	142	260	1285	2345
200	124	126	229	1823	3313	145	265	1459	2658
225	140	132	241	2017	3663	148	271	1630	2966
250	155	140	256	2201	3994	152	277	1796	3265
275	171	150	273	2374	4305	156	284	1958	3556
300	186	161	293	2535	4595	160	292	2117	3843
400	249	227	414	3065	5549	179	326	2709	4908
500	311	355	646	3424	6195	199	363	3238	5860
600	373	614	1118	3643	6589	218	397	3717	6723
700	435	1163	2119	3764	6807	232	423	4161	7522
800	497	2439	4446	3825	6917	241	439	4583	8281
900	559	∞	∞	3853	6967	246	449	4993	9019
1000	621			3865	6989	248	453	5398	9748
1100	684			3869	6996	249	455	5799	10470
1200	746			3870	6998	250	455	6200	11192
1300	808			3871	7000	250	456	6600	11912
1400	870			3871	7000	250	456	7000	12632
1500	932			3871	7000	250	456	7400	13352

INGERSOLL AND ZOBEL SOLUTION

By assuming another condition for (c) in the Kelvin solution, Ingersoll and Zobel [4] obtained a different treatment of the problem. They assumed that the temperature initially increased uniformly with depth, according to the relation determined by Barus,[5] that the melting point of rock varies linearly with pressure (or depth). This initial condition,

$$v = f(x) = mx + v_s \qquad \ldots.(4)$$

when substituted in the solution, gives the derived equation for temperature,

$$v = mx + v_s \cdot \frac{2}{\sqrt{\pi}} \int_0^{\beta} e^{-\beta^2} d\beta, \beta = \frac{x}{2\sqrt{\kappa t}} \qquad \ldots.(5)$$

which is subject to the conditions, $v = 0$ at $x = 0$, for all values of t, and $v = f(x)$ at $t = 0$. In equation (5),

m = rate of increase of melting point of rock with depth in °C. per centimeter.

v_s = initial surface temperature or melting point of rock at the surface of the earth in °C.

When m and x equal zero, equation (5) reduces to equation (1); that is, Kelvin's solution is given from Ingersoll and Zobel's solution, when the term mx is removed and $v_s = v_o$.

Figure 2, plotted from Table 1, column 9, shows the depth-temperature curves of the Ingersoll-Zobel solution, for times corresponding to the curves of Figure 1. *OCD* represents the initial distribution of temperature with *CD* increasing uniformly downward, according to the linear relation $v = mx + v_s$. *OC* represents the temperature of the plane bounding face, being initially, $v_s = 1400°$ C. $= 2552°$ F.; and since a time, $t = 0$, maintained at a constant value, 0° C. The diffusivity $\kappa = 0.0064$, and $m = 0.00004°$ C. per cm. were used to evaluate equation (5). At any given time the temperature at any depth may be read from the curve or interpolated from Table 1, as the table is extended to a point such that the curve is, practically, asymptotic to the line of initial constant temperature *CD*. The line $v = mx$ represents the steady state that will be reached at $t = \infty$, assuming the solid is of infinite length.

[4] L. R. Ingersoll and O. J. Zobel: *op. cit.*

[5] Carl Barus: *High temperature work in igneous fusion and ebullition, chiefly in relation to pressure,* U. S. Geol. Surv., Bull 103 (1893) p. 55.

TABLE 2.—*Age of non-radioactive earth—(Kelvin)*

$\sqrt{\kappa}$ (Diffusivity)	$t \times 10^{-6}$ years			
	$v_o = 7000°$ F. $= 3871.11°$ C.			
	1°F. per 50 ft. 1°C. per 27.4 M.	1°F. per 100 ft. 1°C. per 54.9 M.	1°F. per 150 ft. 1°C. per 82.3 M.	1°F. per 200 ft. 1°C. per 109.7 M.
0.04	711	2,844	6,398	11,375
.05	455	1,820	4,095	7,280
.06	316	1,264	2,844	5,055
.07	232	929	2,089	3,714
.08	178	711	1,600	2,844
.09	140	562	1,264	2,247
.10	114	455	1,024	1,820
.11	94	376	846	1,504
.12	79	316	711	1,264
.13	67	269	606	1,077
.14	58	232	522	929
	$v_o = 3516°$ F. $= 1935.56°$ C.			
0.04	178	711	1,600	2,844
.05	114	455	1,024	1,820
.06	79	316	711	1,264
.07	58	232	522	929
.08	44	178	400	711
.09	35	140	316	562
.10	28	114	256	455
.11	24	94	212	376
.12	20	79	178	316
.13	17	67	151	269
.14	15	58	131	232

The derivative of equation (5),

$$\frac{\partial v}{\partial x} = m + \frac{v_s}{\sqrt{\pi \kappa t}} e - \frac{\chi^2}{4\kappa t} \quad \ldots . (6)$$

gives the geothermal gradient. Reciprocal values of the geothermal gradient for the Ingersoll and Zobel solution are tabulated in Table 1, columns 7 and 8.

When $x = 0$, equation (6) gives the reciprocal gradient at the surface of a non-radioactive earth, computed values of which may be read from Table 3, in terms of diffusivity, m, the rate of increase of melting point with depth, and time. The initial surface temperature is $v_s = 1400°$ C. = 2552° F. An example: When the rate of increase of the melting point of rock, $m = 3°$ C. per kilometer, and the diffusivity is $\sqrt{\kappa} = 0.08$, the reciprocal gradient at the surface is seen from Table 3 to be 213 feet per degree Fahrenheit when the age is $1{,}000 \times 10^6$ years.

Solving equation (6) for t, when $x = 0$,

$$t = \frac{v_s^2}{\pi \kappa \left(\frac{\partial v}{\partial x} - m\right)^2} \quad \ldots . (7)$$

gives the age, $\frac{\partial v}{\partial x}$ being the surface gradient. Equation (7) gives the age of a non-radioactive earth, under the conditions of the Ingersoll and Zobel solution. With a range of diffusivity $\kappa = 0.0016$ to 0.0196 and an assumed value for $v_s = 1400°$ C. = 2552° F.; ages computed from equation (7) may be read in Table 4 for $m = 3°, 4°, 5°$ C. per kilometer, and $\frac{\partial v}{\partial x} = 1°$ F. per 50 feet to 1° F. per 200 feet, or 1° C. per 27.4 meters to 1° C. per 109.7 meters. It is noted, using the assumed conditions for v_s, that an age of $1{,}826 \times 10^6$ years is given in Table 4, for an earth having a surface gradient of 1° F. per 200 feet, a diffusivity of 0.08, and $m = 5°$ C. per kilometer.

APPLICATION OF THE SOLUTIONS

The tables and curves may be used as a basis for an extensive range of values that can readily be determined from the relations of the constants in the equations. The depth-temperature curves of Figures 1 and 2, and the temperatures of both solutions in Table 1, may be used for any value of diffusivity through the relation: the time is inversely proportional to the diffusivity. As an example: changing κ from 0.0064 to 0.0118, the diffusivity used by Kelvin, gives the ratio $0.0064/0.0118 = 0.5424$, which, multiplied by the times of the curves and table, gives 5.4×10^6

years to 1356×10^6 years, thus interpreting the curves and table in terms of the new value for diffusivity.

Similarly, the ages in Table 2 may be interpolated for any value of initial temperature, reciprocal gradient, or diffusivity, as time varies directly as the square of initial temperature, inversely as the square of

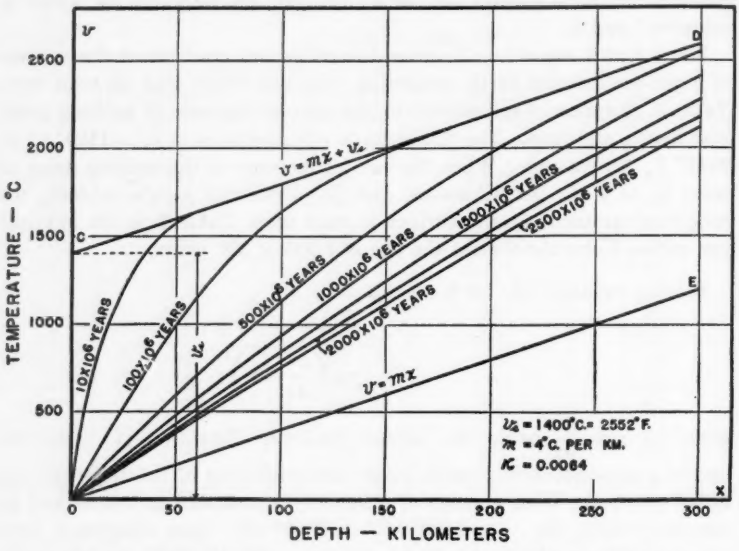

FIGURE 2.—*Depth-temperature curves (Ingersoll and Zobel solution)*

the surface geothermal gradient, and inversely as the diffusivity. The first relation is evident from corresponding columns of $v_o = 3871°$ C. and $v_o = 1936°$ C., as they are for each value of $\sqrt{\kappa}$ numerically, 4/1. The second relation is noted by comparing columns 1° F. per 50 feet and 1° F. per 100 feet, $v_o = 3871°$ C., as they are as 1/4. The relation for diffusivity is noted, as an example, in column 1° F. per 100 feet $v_o = 3871°$ C., for the values $\sqrt{\kappa} = 0.04$ and 0.08. The inverse ratio for the diffusivities, κ, is 4/1, and the time for the smaller value is 4 times the larger. The ages in Table 4 may be extended in like manner, except that time varies inversely as the square of the quantity, surface geothermal gradient minus the rate of increase of melting point, as indicated in equation (7) by $\left(\frac{\partial v}{\partial x} - m\right)^2$. A direct solution from the proportionalities must be made here, as relative values cannot be interpolated directly from the table without using an interpolation formula. As an example: to find t when the reciprocal gradient is 1° F. per 175 feet, $\sqrt{\kappa} = 0.04$, $v_s = 1400°$ C.,

TABLE 3.—*Reciprocal gradients at the surface in non-radioactive earth*

$\sqrt{\frac{1}{\kappa}}$ (Diffusivity)	$v_s = 1400°C$ m = 0.00003°C per cm. = 3°C per kilometer									
	$t = 1000 \times 10^6$ years		$t = 1500 \times 10^6$ years		$t = 2000 \times 10^6$ years		$t = 2500 \times 10^6$ years		$t = 3000 \times 10^6$ years	
	Meters per °C	Feet per °F	Meters per °C	Feet per °F	Meters per °C	Feet per °F	Meters per °C	Feet per °F	Meters per °C	Feet per °F
0.04	70.8	129.1	82.8	150.9	92.1	167.8	99.7	181.7	106.2	193.5
.05	84.1	153.3	97.5	177.6	107.7	196.2	116.0	211.3	122.9	224.1
.06	96.1	175.1	110.5	201.4	121.4	221.2	130.1	237.1	137.4	250.4
.07	106.9	194.9	122.2	222.7	133.5	243.3	142.5	259.7	150.0	273.4
.08	116.9	213.0	132.7	241.8	144.3	263.0	153.5	279.8	161.1	293.6
0.09	125.9	229.5	142.2	259.1	154.0	280.7	163.3	297.6	170.9	311.4
.10	134.3	244.8	150.8	274.9	162.8	296.7	172.1	313.6	179.6	327.4
.11	142.0	258.8	158.7	289.3	170.7	311.1	180.0	328.0	187.5	341.7
.12	149.1	271.8	166.0	302.5	177.9	324.3	187.1	341.1	194.6	354.7
.13	155.8	283.9	172.6	314.7	184.6	336.4	193.7	353.0	201.0	366.4
0.14	161.9	295.1	178.8	325.9	190.6	347.5	199.7	363.9	206.9	377.1
	$v_s = 1400°$ C m = 0.00004° C per cm. = 4° C per kilometer									
0.04	66.2	120.6	76.5	139.4	84.3	153.7	90.7	165.2	96.0	175.0
.05	77.6	141.4	88.8	161.9	97.2	177.2	103.9	189.4	109.5	199.5
.06	87.6	159.7	99.5	181.3	108.2	197.3	115.1	209.8	120.8	220.2
.07	96.6	176.1	108.9	198.4	117.8	214.6	124.7	227.3	130.4	237.7
.08	104.6	190.7	117.1	213.5	126.1	229.8	133.1	242.5	138.7	252.8
0.09	111.9	203.9	124.5	226.9	133.5	243.2	140.4	255.8	145.9	266.0
.10	118.4	215.8	131.1	238.9	140.0	255.1	146.8	267.6	152.3	277.5
.11	124.3	226.6	137.0	249.7	145.8	265.8	152.5	278.0	157.9	287.8
.12	129.8	236.5	142.3	259.4	151.1	275.3	157.6	287.3	162.9	296.9
.13	134.8	245.6	147.2	268.3	155.8	284.0	162.3	295.7	167.4	305.1
0.14	139.4	254.0	151.7	276.4	160.1	291.8	166.4	303.3	171.4	312.4
	$v_s = 1400°$ C m = 0.0005° C per cm. = 5° C per kilometer									
0.04	62.1	113.1	71.0	129.5	77.8	141.7	83.1	151.5	87.6	159.6
.05	72.0	131.2	81.6	148.7	88.6	161.5	94.1	171.6	98.7	179.9
.06	80.6	146.9	90.5	164.9	97.7	178.0	103.2	188.2	107.8	196.4
.07	88.1	160.6	98.2	178.9	105.4	192.0	110.9	202.1	115.4	210.3
.08	94.7	172.6	104.8	191.1	112.0	204.1	117.4	214.1	121.8	222.0
0.09	100.6	183.4	110.7	201.8	117.7	214.6	123.1	224.3	127.4	232.1
.10	105.9	192.9	115.9	211.2	122.8	223.8	128.0	233.3	132.2	240.9
.11	110.6	201.6	120.5	219.6	127.3	231.9	132.3	241.2	136.4	248.5
.12	114.9	209.4	124.6	227.1	131.2	239.2	136.2	248.2	140.1	255.3
.13	118.8	216.5	128.3	233.9	134.8	245.7	139.6	254.5	143.4	261.3
0.14	122.3	222.9	131.7	240.0	138.0	251.6	142.7	260.1	146.3	266.7

TABLE 4.—*Age of non-radioactive earth—(Ingersoll and Zobel)*

$\sqrt{\kappa}$ (Diffusivity)	v_s = 1400°C. = 2552°F.		m = 3°C. per kilometer	
	10^6 years			
	1°F. per 50 ft. 1°C. per 27.4 M.	1°F. per 100 ft. 1°C. per 54.9 M.	1°F. per 150 ft. 1°C. per 82.3 M.	1°F. per 200 ft. 1°C. per 109.7 M
0.04	110	533	1,475	3,306
.05	71	341	944	2,116
.06	49	237	656	1,469
.07	36	174	482	1,080
.08	28	133	369	827
.09	22	105	291	653
.10	18	85	236	529
.11	15	70	195	437
.12	12	59	164	367
.13	10	50	140	313
.14	9	44	120	270
	v_s = 1400°C. = 2552°F.		m = 4°C. per kilometer	
0.04	117	610	1,860	4,726
.05	75	391	1,190	3,024
.06	52	271	827	2,100
.07	38	199	607	1,543
.08	29	153	465	1,181
.09	23	121	367	933
.10	19	98	298	756
.11	16	81	246	625
.12	13	68	207	525
.13	11	58	176	447
.14	10	50	152	386
	v_s = 1400°C. = 2552°F.		m = 5°C. per kilometer	
0.04	125	706	2,416	7,303
.05	80	452	1,546	4,674
.06	56	314	1,074	3,246
.07	41	231	789	2,385
.08	31	177	604	1,826
.09	25	140	477	1,443
.10	20	113	387	1,168
.11	17	93	319	966
.12	14	78	268	811
.13	12	67	229	691
.14	10	58	197	596

$m = 3°$ C. per kilometer. The reciprocal gradient 1° F. per 175 feet is equal to 1° C. per 96.0 meters, and the gradient equals 0.0001042° C. per cm. The reciprocal gradient 1° F. per 150 feet is equal to 1° C. per 82.3 meters, and the gradient equals 0.0001215° C. per cm. The proportion is,

$$\frac{(0.0001215 - 0.00003)^2}{(0.0001042 - 0.00003)^2} = \frac{t}{1475 \times 10^6}$$

Solving, $t = 2243 \times 10^6$ years for a reciprocal gradient of 1° F. in 175 feet.

Table 3 may be interpolated linearly for other diffusivities than those tabulated, to obtain a relative value for the reciprocal gradient; but interpolation for time involves either the use of higher order differences, or an extended computation to obtain a comparative value. A direct solution may be made to interpolate other values of v_s by the relation: the quantity, geothermal gradient minus the rate of increase of melting point, varies directly as the initial surface temperature. As an illustration: to find the change in the reciprocal gradient when $v_s = 1200°$ C. for $\sqrt{\kappa} = 0.08$, $t = 1500 \times 10^6$ years, $m = 0.00003°$ C. per cm. The reciprocal gradient 132.7 meters per °C., equals 0.00007536 °C. per cm. The proportion is,

$$\frac{0.00007536 - 0.00003}{\frac{\partial v}{\partial x} - 0.00003} = \frac{1400°}{1200°}$$

$$\frac{\partial v}{\partial x} = 0.0000689° \text{ C. per cm.}$$

$$= 0.00689° \text{ C. per meter.}$$

The reciprocal gradient = 145.1 meters per °C = 264.5 feet per °F. (1° C. per meter = 1° F. in 1.82269 feet; 1° C. per foot = 1° C. in 0.54864 meters.)

Other interpolations may be made from the equations, if desired, but the main object of the paper is to show how certain assumptions work out in actual figures. The curves, tables, and suggested proportionalities inherent in the equations of the two solutions, enable an age, temperature, or reciprocal geothermal gradient in a non-radioactive earth to be read directly, or quickly interpolated, for different assumed initial values of the constants in either solution. Equation (1) with Tables 1 and 2, and Figure 1, may be used in the solution of the heat conduction problem of any semi-infinite solid that satisfies the boundary conditions given for this equation.

CONCLUSIONS

Normal cooling of the earth is a possibility, with the primitive heat brought to the surface by conduction, as no conclusive proof has been advanced that the thermal energy assigned to radioactivity, effects of condensation, chemical reactions, and crystallization, generate the temperatures in the crust of the earth. The observed temperatures and calculated thermal gradients [6] do not necessarily indicate that the crust is being heated, and the temperature rising, as would be the case if theoretical calculations [7] and laboratory determinations [8] were accepted for the amount of heat that is generated by radioactivity and other means in the crust or surface layers.

Results by Sosman,[9] Evans,[10] Nansen,[11] Krige and Pirow,[12] and Johnston,[13] are negative as to heat generation in the crust. Daly [14] suggests that cosmic rays may be responsible for the instability of the atom. Consequently, radioactivity would be confined to a superficial layer, due to the absorption of the cosmic rays by the rock. However, the sub-atomic processes by which cosmic rays are generated and their effect on other substances are not fully understood.

The real meaning of the observed geothermal gradients is yet unanswered, as is the correlation of these gradients with geological facts, and with the conductivity of the rocks and strata. Local rocks may be low in radiothermal heat below the sedimentary layer, or the radioactive layer may be thin. The conclusion proposed by De Lury [15] is that the lowest measured geothermal gradient should be used for earth age determination, rather than the highest, or the so-called average, gradient.

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[6] C. E. Van Orstrand: *Temperature gradients* in *Problems in petroleum geology*, Am. Assoc. Petr. Geol., Sidney Power's memorial volume (1934) p. 989-1021.

[7] John Joly: *Surface history of the earth*, p. 60. The Clarendon Press.

[8] C. B. Thwing: *Measurements of the internal temperature gradient in common materials*, Phys. Rev., vol. 23 (1906) p. 315-320.

G. B. Pegram and H. W. Webb: *Heat developed in a mass of thorium oxide, due to its radioactivity*, Phys. Rev., vol. 26 (1908) p. 410; vol. 27 (1908) p. 18-26.

Harold Jeffreys: *The earth, its origin, history, and physical constitution* (1929) p. 141-144. The Macmillan Company, New York, 2d ed., rev.

J. H. J. Poole and John Joly: *Radioactivity of basalt and other rocks*, Philos. Mag., vol. 48 (1924) p. 819.

[9] R. B. Sosman: *General summary of the symposium on hot springs*, Jour. Geol., vol. 32 (1924) p. 468-469.

[10] J. W. Evans: *Radioactivity and the heat of the earth*, Nature, vol. 119 (1927) p. 424-425.

[11] F. Nansen: *The earth's crust, its surface forms, and isostatic adjustment*, Avhand. utgitt av Der Norske Videnskaps-Akad. i Oslo, 1 Mat. Naturv Klasse, no. 12 (1928) p. 20-21.

[12] L. J. Krige and H. Pirow: *Temperature measurements in the Dubbledevlei bore hole, Carnarvon district*, Geol. Soc. S. Africa, Tr., vol. 26 (1923) p. 61.

[13] W. D. Johnston, Jr.: *Geothermal gradient at Grass Valley, California*, Wash. Acad. Sci., Jour., vol. 22, no. 10 (1932) p. 267-271.

[14] R. A. Daly: *Igneous rocks and the depths of the earth* (1933) p. 221. McGraw-Hill, New York.

[15] J. S. De Lury: *Thermal history of the crust*, Royal Soc. Canada, Tr., vol. 4 (1932) p. 277-288; *The strength of the earth*, Jour. Geol., vol. 41, no. 7 (1933) p. 748-755.

Van Orstrand [16] has indicated that an age of the earth may be obtained by the use of thermal methods comparable to that obtained by other methods.

With an assumed geothermal gradient of 1° F. per 200 feet and a diffusivity of $\sqrt{\kappa} = 0.08$, an age of $2{,}844 \times 10^6$ years is read from Table 2, the Kelvin solution. If m = 5° C. per kilometer, using the same assumed geothermal gradient and diffusivity, an age of $1{,}826 \times 10^6$ years is read from Table 4, the Ingersoll-Zobel solution. A small change of diffusivity to $\sqrt{\kappa} = 0.07$, a not improbable average, increases the age to $3{,}714 \times 10^6$ and $2{,}385 \times 10^6$ years respectively for the solutions. Johnston [17] has found a gradient of 1° F. per 189.8 feet at Grass Valley, California. Using Table 3, with m = 5° C. per kilometer and a diffusivity $\sqrt{\kappa} = 0.07$, an age of approximately 2000×10^6 years is read. De Lury [18] gives a geothermal gradient of 1° F. per 233.2 feet (recomputed from the original data given by Cleland,[19] using least squares) for the McIntyre mine in northern Ontario, Canada. With the assumed values the same as those in the preceding example, the age is seen to be more than $3{,}000 \times 10^6$ years.

The above tables and figures may be used for comparison with the partial solutions of the radioactive earth presented by Ingersoll and Zobel,[20] Holmes,[21] Jeffreys,[22] and Lowan.[23]

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[16] C. E. Van Orstrand: *Normal geothermal gradient in the United States*, Am. Assoc. Petr. Geol., Bull., vol. 19, no. 1 (1935) p. 78-115.

[17] W. D. Johnston, Jr.: *op. cit.*

[18] J. S. De Lury: *Thermal history of the crust*, Royal Soc. Canada, Tr., vol. 4 (1932) p. 279.

[19] R. H. Cleland: *Rock temperatures and some ventilation conditions in the mines of northern Ontario*, Canad. Min. Metall. Bull., no. 256 (1933) p. 379-407.

[20] L. R. Ingersoll and O. J. Zobel: *Mathematical theory of heat conduction* (1913) p. 90-96.

[21] Arthur Holmes: *Radioactivity and the earth's thermal history*, Geol. Mag., dec. 6, vol. 2 (1915) p. 102-112.

[22] Harold Jeffreys: *op. cit.*, p. 148-150.

[23] A. N. Lowan: *Cooling of a radioactive sphere*, Phys. Rev., vol. 44, no. 9 (1933) p. 769-775; with note, vol. 45, no. 12 (1934) p. 899.

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MARTINSBURG LIMESTONES IN EASTERN PENNSYLVANIA

BY RALPH L. MILLER

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INTRODUCTION

The Martinsburg formation consists of a thick series of shales and sandstones of upper Trenton and Cincinnatian age. Within the main belt of the Martinsburg in the Lehigh and Lebanon valleys of eastern Pennsylvania (Fig. 1) are many exposures of unfossiliferous limestone varying in thickness from a few inches to 160 feet. In a number of places the limestone is sufficiently abundant and of such a quality as to have permitted quarrying for lime or for road metal. Eighteen such limestone areas appear on the Geologic Map of Pennsylvania (1931). In a comprehensive paper discussing general Martinsburg relations, Stose

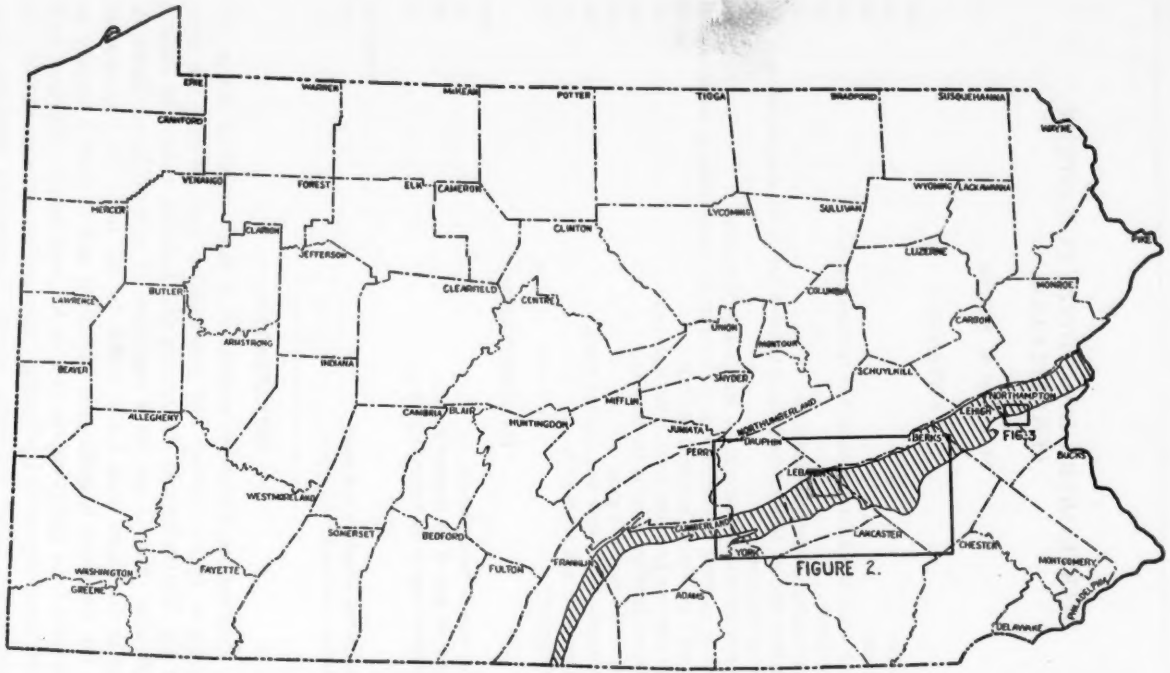

FIGURE 1.—*Index map of Pennsylvania*

Showing the Martinsburg belt along the Great Valley (shaded), and the location of the two limestone areas within the shale belt (Figs. 2 and 3) described in this paper.

and Jonas [1] mention several of these areas near the Schuylkill River and interpret them as anticlines of the Leesport limestone, exposed by erosion of the overlying shale. They also consider other areas shown on the state geologic map to be anticlinal inliers of Leesport.[2] On the other hand, Behre [3] mentions interbedding of limestone within the Martinsburg formation as being well shown in the same Schuylkill River region.

In the vicinity of Harrisburg, Stose [4] describes limestones "near and at the base of the (Martinsburg) formation." Those near, but not at, the base must be interbedded in the lower part of the Martinsburg. The Leesport, as described by Stose and Jonas,[5] contains considerable interbedded shale. Where the limestone is more conspicuous than the shale, the authors assign it to the Leesport formation; where the opposite is true, the limestone is considered Martinsburg.[6]

Limestones cropping out within the shale belt in the region east of the Lehigh River have been described by Miller [7] and Behre [8] and have been interpreted as being interbedded with the Martinsburg shales. In a later report, Behre [9] considers the possibility that these limestones may be Conococheague (Upper Cambrian) in fault or unconformable contact with the shale. Stose and Jonas [10] also favor this view.

In studying and mapping the geology of the Jacksonburg-Leesport limestone belt, the writer encountered the problem of the stratigraphic position of the limestones which crop out within the Martinsburg shale belt. All the known limestone areas in the shale belt were visited and many new ones were discovered. In a number of the areas, the evidence seems to prove interbedding of the limestone with the shales of the Martinsburg formation; in almost all the other areas, this interpretation is strongly favored. The stratigraphic position of these limestones bears closely on unsettled problems involving the structure and stratigraphy of the whole Martinsburg shale belt. It has, therefore, seemed advisable to present in some detail the evidence and reasoning which governed the foregoing conclusions.

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[1] G. W. Stose and A. I. Jonas: *Ordovician shales and associated lava in southeastern Pennsylvania*, Geol. Soc. Am., Bull., vol. 38 (1927) p. 511.

[2] Personal communication.

[3] C. H. Behre, Jr.: *Slate in Pennsylvania*, Pa. Geol. Surv., Bull. M 16 (1933) p. 139.

[4] G. W. Stose: *Unconformity at the base of the Silurian in southeastern Pennsylvania*, Geol. Soc. Am., Bull., vol. 41 (1930) p. 638.

[5] G. W. Stose and A. I. Jonas: *op. cit.*, p. 511.

[6] *Op. cit.*, p. 509.

[7] B. L. Miller: *Mineral resources of the Allentown quadrangle, Pennsylvania*, Pa. Geol. Surv., Topog. and Geol. Atlas, no. 206 (1925) p. 130.

[8] C. H. Behre, Jr.: *Slate in Northampton County, Pennsylvania*, Pa. Geol. Surv., Bull. M 9 (1927) p. 21-23.

[9] C. H. Behre, Jr.: *Slate in Pennsylvania*, Pa. Geol. Surv., Bull. M-16 (1933) p. 135-136.

[10] G. W. Stose and A. I. Jonas: *op. cit.*, p. 513.

STRATIGRAPHY

The formations represented in the Lehigh and the Lebanon valleys, with which this paper is concerned, may be grouped together for purposes of general description in the following manner:

Martinsburg shale, 3000–11,000 (?) feet
Jacksonburg-Leesport-Chambersburg limestone, 0–600 feet
Beekmantown and Cambrian limestones and dolomites, 3700 feet

The Cambrian and Beekmantown formations are massive-bedded limestones and dolomites, usually white, buff, or gray. The massive nature of the bedding is an almost unfailing identifying character, as is the absence of shaly material. The Jacksonburg-Leesport-Chambersburg limestones may not be exact stratigraphic equivalents but they occupy the same stratigraphic interval and no two of them are found in the same region. They are listed in order from east to west. As represented on the Geologic Map of Pennsylvania (1931), the Jacksonburg is found from the Lehigh River eastward into New Jersey, the Leesport from the Lehigh River westward to the Susquehanna River at Harrisburg, and the Chambersburg from Harrisburg southwestward to the Maryland border. These three formations are, in general, thin-bedded, non-dolomitic limestones; east of Harrisburg they are notably argillaceous over large areas, but very rarely contain pure shale beds or partings. The Martinsburg formation is a thick shale series, locally metamorphosed to slate. In the Harrisburg region, Stose [11] has recognized two members, a lower shale member, and an upper sandy member, with a total thickness of 3000 feet. In the eastern part of the state, Behre [12] and Miller [13] recognize three members: a lower and an upper shale (or slate) separated by a middle sandy member, with an estimated thickness of 11,000 feet. Stose [14] believes the upper member is a repetition of the lower member by folding. This discrepancy in interpretation and in estimated thickness is a reflection of the extreme complexity of structure within the shale belt and of the difficulty in recognizing or following key beds from one region to another.

Topographically, the Cambrian and Beekmantown limestones form a continuous lowland, 1 to 5 miles wide along the southeast side of the Great Valley, here known as the Lehigh and the Lebanon valleys. Along the northwest side of the Great Valley, the Martinsburg shales form another continuous belt at a higher elevation, the upper level of which is usually referred to as the Harrisburg peneplane. The shale belt varies

[11] G. W. Stose: *op. cit.*, p. 632, 634.
[12] C. H. Behre, Jr.: *Slate in Pensylvania*, Pa. Geol. Surv., Bull. M-16 (1933) p. 136-137.
[13] B. L. Miller: *op. cit.*, p. 130.
[14] G. W. Stose: *op. cit.*, p. 634.

in width from 6 to 12 miles. Between these two, the Jacksonburg-Leesport-Chambersburg limestones crop out in a discontinuous belt reaching a maximum of 2 miles in width. These formations lie along the northwestern edge of the limestone lowland, the major part of which is underlain by the Cambrian and the Beekmantown.

LIMESTONE AREAS IN MARTINSBURG SHALE BELT (WESTERN REGION)

DESCRIPTION

Detached limestone areas lying entirely within the Martinsburg shale belt are found in two separate regions, one from the vicinity of Kutztown westward to Harrisburg (Fig. 2), and the other near Seemsville east of the Lehigh River (Fig. 3). The character and field relations of the western and the eastern regions are somewhat different and will be discussed separately.

In the western region, the map (Fig. 2) shows all the areas where more than one foot of limestone has been found cropping out in the shale belt. The total number of limestone exposures indicated is 78. In a few cases, several exposures that are known or thought to lie along the line of outcrop of the same limestone belt have been marked separately on the map. Each dot on the map does not, therefore, represent an isolated limestone area. As the writer has found many previously unreported belts of limestone outcrop, he suggests that others may exist in areas that have not been studied, particularly west of the Susquehanna River. Within those parts of the region that have been traversed only on roads, there are probably more limestone areas; others may be concealed by cover.

The greatest thickness of limestone measured in a continuous section is 160 feet at Harpers Tavern in the Hummelstown quadrangle (Fig. 2, no. 7). Another thick section of 66 feet is exposed in a quarry in the Reading quadrangle, 0.4 mile N33°W of Dauberville (Fig. 2, no. 33). Although no limestone belt was followed with certainty for more than 2½ miles, several are thought to be continuous for distances of 4 or 5 miles, across areas having infrequent exposures.

INTERBEDDING OF LIMESTONE AND SHALE

Interbedding of the limestones with the Martinsburg shales is seen in a number of exposures. Four fairly distinct varieties of this interbedding occur; however, there are gradations from one type to another.

In the first type, a few beds of light-gray, fine-grained, pure limestone are interlayered with the shale. In some places there is but a single bed of limestone; elsewhere, several thin beds are separated by much greater thicknesses of shale. The limestone beds weather lighter in color and usually stand out prominently in a quarry face or roadcut. Indi-

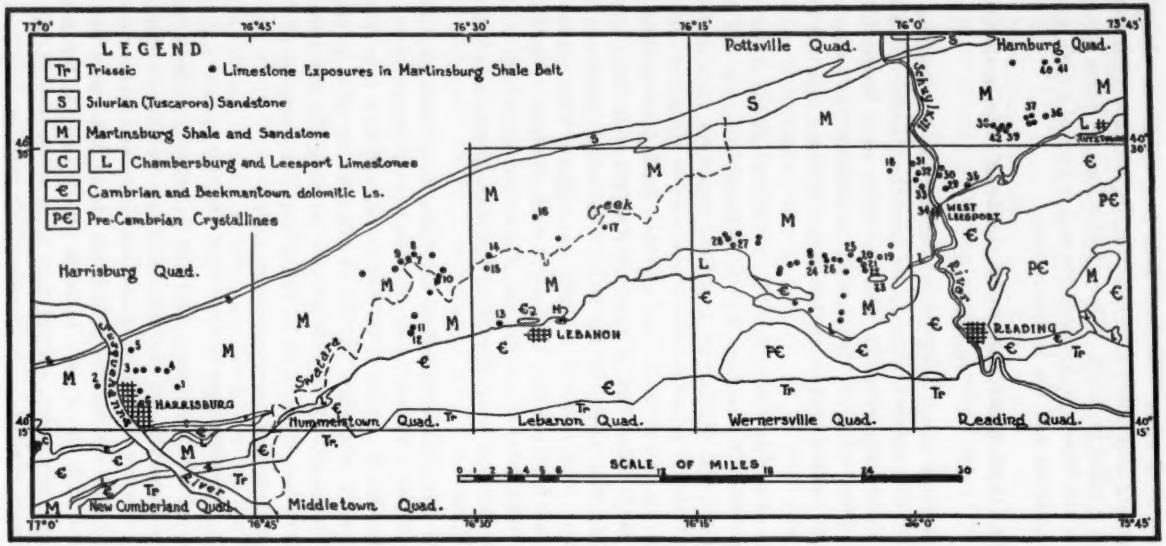

FIGURE 2.—*Geological map of the western region*

Showing limestone exposures within the Martinsburg shale belt. Geologic boundaries taken from the Geologic Map of Pennsylvania (1931), with modifications by the author.

vidual beds are not persistent for long distances, but thin out rapidly. The total amount of limestone in exposures of this type is negligible. The evidence presented by the occurrences is valuable, however, in demonstrating the occasional deposition of pure limestone in Martinsburg

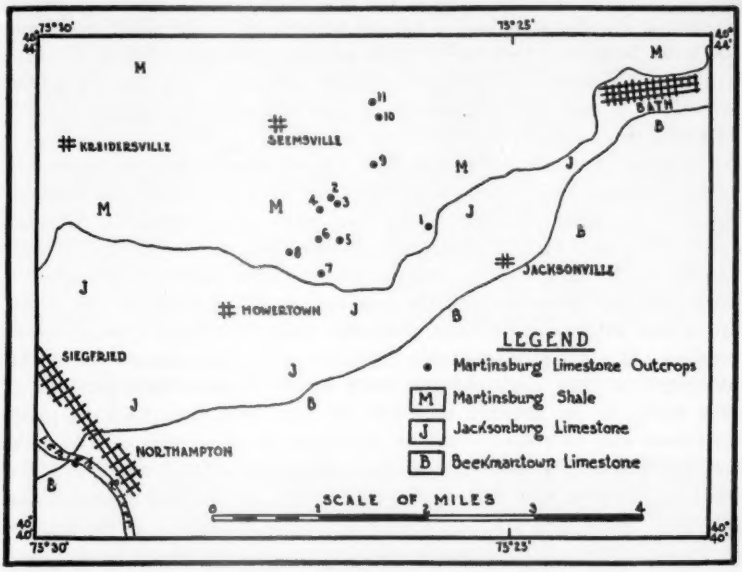

FIGURE 3.—*Geological map of the eastern region*
Showing exposures of limestone within the Martinsburg shale belt.

time. Places in which interbedding of this type may be seen are numerous, especially in the region near the Schuylkill River. A good example is in a large shale quarry 0.5 mile S12°W of Hecktown School in the Reading quadrangle (Fig. 2, no. 35), and another in a roadcut 0.65 mile S46°E of Obold in the Wernersville quadrangle (Fig. 2, no. 20).

A second type of interbedding consists of 2- to 6-inch beds of high-grade limestone separated by shale layers of about equal thickness. This is not a common lithology but it has been found in a few places; an example is seen in a large quarry 0.9 mile S46°E of Obold in the Wernersville quadrangle (Fig. 2, no. 21).

Beds of platy limestone, 1 to 3 inches thick, separated by thin shale partings, constitute the most common type of interbedding. This lithology has been found in many places, several of which contain more than 50 feet of limestone. Some fine exposures exist where limestone of this character passes into homogeneous Martinsburg shale both downward

and upward, without the possibility of folding or faulting. This change takes place by increase in the thickness of the shale partings and decrease in the abundance of the limestone beds until shale alone remains. A good example is exposed in a roadcut 0.35 mile S35°E of Mohrsville in the Reading quadrangle (Fig. 2, no. 30; Pl. 1, fig. 1), and another in the cut of the Lebanon and Tremont branch of the Reading Railroad, 100 miles N82°W of Coheva in the Lebanon quadrangle (Fig. 2, no. 13). A greater thickness of limestone of this type, with marginal relations concealed, is exposed in a quarry in the Wernersville quadrangle, 0.8 mile S63°W of Centerport (Fig. 2, no. 18; Pl. 1, fig. 2).

The fourth type of interbedding consists of massive beds of limestone or sandy limestone, from 1 to 8 feet thick, with occasional shale layers about a foot thick. This may be seen above the entrance to Crystal Cave, 1.7 miles N90°E of Virginville, in the Hamburg quadrangle (Fig. 2, no. 36; Pl. 2, fig. 1). Here, and at several other localities, the massive limestone beds give way at the top and at the bottom to the platy limestones with shale partings, described under the third type of interbedding. At especially favorable exposures there is gradation across the bedding from pure shale through platy limestone with shale partings of type three, to the massive limestone of type four, then back to platy limestone and to shale. Such is an exposure in a roadcut 0.65 mile S46°E of Obold, in the Wernersville quadrangle (Fig. 2, no. 20). The massive limestone beds are locally quite sandy. They may show striking edgewise conglomerate with the broken limestone beds in a sandy limestone matrix; the latter is particularly common in the Harrisburg region.

STRATIGRAPHIC POSITION OF LIMESTONE AREAS IN THE SHALE BELT OF THE WESTERN REGION

GENERAL STATEMENT

Most of the limestone belts in the western region display interbedding of one or more of the four types described. For reasons to be discussed these are believed to lie within the Martinsburg, and the Leesport designation is rejected. They are interpreted as lenses of limestone deposited at different times subsequent to the deposition of the oldest Martinsburg shale. The reasons supporting this determination are arranged in two groups: those directly indicating a Martinsburg equivalence, and those opposing a Leesport equivalence (or Chambersburg, for those in the Harrisburg region).

REASONS FAVORING INCLUSION IN THE MARTINSBURG FORMATION

1. In some localities thin beds of limestone are found in the Martinsburg shales.

2. Complete exposures of more extensive limestone have shown gradation into homogeneous shales at the bottom and at the top.

FIGURE 1. ROADCUT NEAR MOHRSVILLE IN THE READING QUADRANGLE
Showing limestone beds (LS) with shale partings grading upward at the right and downward at the left into homogeneous shales.

FIGURE 2. QUARRY 0.8 MILE S 63° W OF CENTERPORT IN THE WERNERSVILLE QUADRANGLE
Showing typical platy limestones separated by shale partings.

INTERBEDDED LIMESTONE AND SHALE

FIGURE 1. EXPOSURE ABOVE ENTRANCE TO CRYSTAL CAVE IN HAMBURG QUADRANGLE
One-foot shale layer (under hammer head) intercalated between massive limestone beds. Massive limestones grade upward into platy limestones with shale partings.

FIGURE 2. EXPOSURE ALONG SWATARA CREEK AT HARPERS TAVERN
Dark-colored limestone beds (left) have been eroded off crest of anticline of light-colored shale. Axis of anticline plunges steeply toward lower left of picture. (Photo by Bradford Willard.)

LITHOLOGIC AND STRUCTURAL TYPES

3. The lithology of the limestone in exposures that do not show the marginal relations to the shales can be matched by similar lithologies in exposures that show gradation into shale at the top and at the bottom.

REASONS OPPOSING CORRELATION WITH THE LEESPORT (OR CHAMBERSBURG) LIMESTONE

1. In some localities, the limestone beds are steeply dipping and limited on both sides by nearby shale outcrops; thus, the limestone is almost completely exposed. If this be Leesport, it necessitates isoclinal folding with repetition of beds on opposite sides of the axial plane. Nowhere has this doubling back and repetition of beds been observed by the author.

2. In a few exposures, shale underlies the limestone in such a fashion as to make anticlinal upfolding of Leesport impossible. For example, at Harpers Tavern in the Lebanon quadrangle (Fig. 2, no. 7), 160 feet of limestone is folded into an open anticline, the core of which is composed of shale of unknown thickness (Pl. 2, fig. 2).

3. Some of the limestones several miles north of the southern margin of the shale belt lie in close proximity to, or in actual contact with, red shales. The latter are not uncommon in the Martinsburg formation, especially in the higher parts of the shale series. Red and purple shales have been described by Stose and Jonas [15] in the lower part, at several localities that lie outside the area studied by the author. In mapping the boundary along the southern margin of the shale belt, from the New Jersey border westward for 130 miles to Hummelstown, and in visiting several exposures from Hummelstown to Harrisburg, the author saw no red shales at, or within several score feet of, the base of the Martinsburg. Where not completely absent, red shales are rarely and sparingly found in the lowest part of the Martinsburg in this region. Thus, it would seem that the limestones in contact with, or in close proximity to, abundant red Martinsburg shales are not Leesport limestones brought to the surface by folding.

4. The Leesport limestone is thin-bedded, dark, and argillaceous. From the Schuylkill River eastward, the contact of the Leesport with the Martinsburg shale is an unconformity, and there is no gradation or interbedding from the limestones upward into the shales. The author has observed no pure shale or shale partings between limestone beds in the Leesport in this region. From the Schuylkill River to the Susquehanna River, good exposures are rare, and there is considerable doubt as to the nature of the contact between the Leesport and the Martinsburg. Stose and Jonas [16] believe shale is interbedded with the limestone in the

[15] G. W. Stose and A. I. Jonas: *Ordovician shales and associated lava in southeastern Pennsylvania*, Geol. Soc. Am., Bull., vol. 38 (1927) p. 514, 516, 521, 522, 526.

[16] *Op. cit.*, p. 510, 511.

Leesport formation, perhaps in considerable quantities. This view is based, in part, on studies outside the limits of the area considered in this paper. In his work along the main belt of the Leesport limestone west of the Schuylkill River, the author has found interbedded shale or shale partings between limestone beds at only two localities. In each of these the section is confused, and there seems reason to doubt that the beds belong within the Leesport formation. The two localities are the Reading Railroad cut at West Leesport in the Reading quadrangle (Fig. 2, no. 34) and the cut of the Lebanon and Tremont branch of the Reading Railroad, 0.8 mile west of Coheva, in the Lebanon quadrangle [17] (Fig. 2, no. 13). Positive conclusions are impossible where exposures are so poor. It seems safe to state, however, that shale beds, or even shale partings, are rare within the Leesport formation along the main limestone belt. In the limestone exposures lying entirely within the Martinsburg belt, shale partings and interbedded shale layers are the rule. Furthermore, the Leesport limestone in the main limestone belt is dark-colored and argillaceous, whereas the limestones within the Martinsburg belt are commonly light-colored, dense, pure, and platy. The designation of limestone areas within the Martinsburg belt as Leesport would demand that lithologic changes in the formation take place consistently along, or near, the southern margin of the shale belt, a fortuitous boundary insofar as original conditions of sedimentation are concerned. Therefore, it seems unlikely, on lithologic grounds, that the limestones within the Martinsburg belt belong in the Leesport formation.

The first and third reasons listed above for opposing the Leesport designation for the limestones lose their validity if upfaulting, rather than upfolding, be invoked. This interpretation has not been advanced by any previous workers to explain the limestone areas now under discussion, nor has the author seen evidence suggesting faults of large displacement near the limestones. In some cases, marginal relations are sufficiently exposed to preclude the possibility of faulting. In other cases, dips and strikes in the limestone, similar to those in nearby shale outcrops, render faulting unlikely. The other reasons for opposing a Leesport designation are as applicable in the case of upfaulting as of upfolding.

CRYSTAL CAVE-ONYX CAVE LIMESTONE BELT

The belt of limestone, in which both Crystal Cave (Fig. 2, no. 36) and Onyx Cave (Fig. 2, no. 38) lie, deserves special mention. A series of quarries and exposures, from Crystal Cave westward to Onyx Cave, indicate that this is a continuous limestone belt. The limestone is about

[17] A complete discussion of these sections must be reserved for the paper on the Jacksonburg and the Leesport limestones now in preparation.

100 feet thick and is, for the most part, massive-bedded and siliceous. At Crystal Cave, the beds are steeply dipping, contain a 1-foot interbedded shale layer, and pass upward into platy limestone with shale partings (Pl. 2, fig. 1). Shale outcrops, with similar dip and strike, are found within 100 feet on both sides of the limestone belt. This evidence favors a Martinsburg age. At Onyx Cave, and in several of the intervening quarries where marginal relations are concealed, the massive beds of siliceous limestone might suggest a Beekmantown age. However, in a roadcut and quarry (Fig. 2, no. 39) near Onyx Cave, shale underlies the massive limestone, with a 10-foot transitional zone of interbedded platy limestone and shale. Between this exposure and Onyx Cave, hillside ledges (Fig. 2, no. 42) of massive limestone pass upward into shale, through a platy limestone zone 15 feet thick. The evidence at Crystal Cave, the continuity of the limestone belt between the two caves, and the cumulative evidence in several exposures near Onyx Cave, indicate that the whole belt is probably Martinsburg limestone, but of a lithology not common to the Martinsburg limestones in the western region.

BEEKMANTOWN LIMESTONE AREAS IN THE SHALE BELT

In the western region are four limestone areas, characterized by massive beds without shaly partings or shale layers. These have not been included in the foregoing discussion. Their boundary relations with the surrounding shales are not similar to those already described, or else they cannot be observed. Lithologically, the limestone in these areas is unlike the Leesport. It closely resembles the Beekmantown or the Upper Cambrian limestone in the massive bedding, in the presence of dolomite, and in the character of the weathering. The Leesport limestone does not form a continuous belt along the south margin of the Martinsburg shales (Fig. 2); therefore, the Beekmantown may be folded or faulted into the shale belt without exposing any Leesport. Stose and Jonas [18] have carefully described the complex structure of one of these areas just south of Jonestown, in the Lebanon quadrangle. They suggest a Beekmantown age for the limestone (Fig. 2, nos. 14 and 15), with anticlinal folding as the major structure, although the section has been repeated by a normal fault. The author's observations on the character of the limestone are in accord with the Beekmantown designation.

Lithologic considerations and areal distribution, as shown by detailed mapping, indicate a Beekmantown age for the area at Hiesters Mill in the Wernersville quadrangle (Fig. 2, no. 23). This area is barely cut off from an anticlinal valley of Beekmantown limestone projecting into the shale belt. Along the south margin of this limestone area, a narrow

[18] G. W. Stose and A. I. Jonas: *op. cit.*, p. 526-534.

belt of typical Leesport limestone crops out. In the Reading quadrangle, the limestone area 0.5 mile N80°W of Gernant Church (Fig. 2, no. 29) may be Beekmantown. The lithology is quite like the Beekmantown but, due to the limited exposures, corroborative or contradictory structural evidence is lacking. There is another area of probable Beekmantown limestone in the Wernersville quadrangle; the rock is well exposed in a quarry 0.2 mile south of Host (Fig. 2, no. 28). The limestone is massive-bedded, partly dolomitic, and resembles neither the Leesport nor the Martinsburg limestones. The structure in this area is not clear, but the situation seems best explained by a northwest-trending fault with upthrow on the northeast side.

One area, showing limestone of a different character from any previously described, has been found within the shale belt. The area is roughly triangular in shape, a quarter of a mile in longest dimension. The rock is well exposed in a small abandoned quarry 1.6 miles S66°E of Snyder in the Hummelstown quadrangle (Fig. 2, no. 12). It is a mottled, very pure crystalline limestone, identical with that developed 1 mile southward in the main limestone belt. The latter has been mapped as Leesport on the Geologic Map of Pennsylvania (1931). Stose and Jonas [19] believe it is either Stones River in age or a pure limestone facies of the Beekmantown. The author agrees that it is not Leesport, and tends to favor the Beekmantown designation. The lithology of the limestone in the area lying within the Martinsburg belt is so distinctive and so different from the Martinsburg limestones that it is excluded from the Martinsburg without hesitation and is referred to the Beekmantown or Stones River. The structure seems to be anticlinal folding, with normal faulting on the east side of the area along Quittapahilla Creek.

Another area of the same limestone lies just north of Lebanon (Fig. 2). This area does not need special consideration, as it is barely cut off from the main limestone belt by a narrow tongue of Martinsburg shale and may not, in fact, be completely isolated.

LEESPORT LIMESTONE AREAS IN THE SHALE BELT

Five areas within the Martinsburg belt, referred to the Beekmantown, suggest that Leesport inliers might also be expected. The only locality where the author has found Leesport is at Hiesters Mill, already described, where it is exposed along the south side of the Beekmantown inlier. The absence of a larger number of Leesport inliers may be explained when the areal distribution of the Leesport along the main limestone belt is considered. The author's detailed mapping from Kutztown to Hummeltown (Fig. 2) has shown that the Leesport is

[19] *Op. cit.*, p. 509.

found beneath the Martinsburg for less than half this distance.[20] It is to be expected, therefore, that there should be more Beekmantown than Leesport inliers within the Martinsburg belt.

As described by Stose and Jonas, the Leesport contains considerable quantities of interbedded shale. If this be true, several poorly exposed limestone areas in the shale belt, which do not have the usual distinctive Martinsburg limestone lithology, might be designated as Leesport. The author has already stated his reason for believing that the Leesport rarely contains interbedded shale. He has, therefore, referred these incompletely exposed areas to the Martinsburg, although the other possibility cannot be eliminated.

SUMMARY OF THE WESTERN REGION

The author's evidence has indicated that a large majority of the limestone areas in the Martinsburg shale belt belong in the Martinsburg formation. Table 1 indicates the more important limestone exposures. Distances are airline, scaled with bearings from the topographic maps, and measured from the most central crossroad in each town indicated. Those limestone exposures that definitely grade into shale at the top and at the bottom are checked as Martinsburg. Where other lines of evidence favor a Martinsburg designation, exposures are checked as probably Martinsburg. All the limestone areas that are believed to be other than Martinsburg, or whose classification is doubtful, are included in the list. The thicknesses given represent the amount of limestone exposed, which in most cases is not the maximum thickness.

Many more limestone areas have been located (Fig. 2) than are shown on the small scale geologic maps of the region. On the other hand, no limestone was found by the author in several areas where its presence has been indicated on the Geologic Map of Pennsylvania (1931). In the Lebanon quadrangle, the large area mapped as Leesport around Fredericksburg was almost entirely underlain by shale. Only 1 foot of limestone (Fig. 2, no. 16) was found exposed in the midst of abundant shale outcrops. In the two areas also mapped as Leesport, which lie 3 miles west of Fredericksburg, shale crops out along the roads at close intervals, with no limestone exposed. Several areas in the Hummelstown quadrangle revealed no limestone exposures; in some of these, there were abundant shale outcrops. In such cases, limestone may have been correctly reported—perhaps from well records—but it must exist only in small areas. The author believes its extent and areal importance are greatly exaggerated on the State Geologic Map. He finds no warrant

[20] This mapping excludes from the Leesport the pure crystalline limestone around Lebanon which is shown on the State Map as Leesport, but which Stose and Jonas (personal communication) and the author believe to be Stones River or Beekmantown.

TABLE 1.—*Limestone exposures in the shale belt (western region)*

Locality*	Martinsburg	Probably Martinsburg	Beekmantown	Leesport	Thickness (feet)
HARRISBURG QUADRANGLE					
1. Quarry 0.35 mile N13° E of Progress	.....	x	.....	.....	74
2. Railroad cut 0.7 mile S20° W of Enola	.....	x	.....	.....	110
3. Bluff 1 mile S60° E of Coxtown, perhaps same belt as 2	.....	x	.....	.....	250
4. Bluff 2.7 miles S78° E of Coxtown, same belt as 3	.....	x	.....	.....	108
5. Bluff 0.2 mile N50° E of Lucknow	.....	x	.....	.....	125
6. Roadcut on Herr St. at 13th in Harrisburg	.....	x	.....	.....	112?
HUMMELSTOWN QUADRANGLE					
7. Bluff along Swatara Creek 0.25 mile east of Harpers Tavern	.....	x	.....	.....	160
8. Quarry 0.7 mile N60° E of Harpers Tavern, same belt as 7	.....	x	.....	.....	5
9. Roadcut 0.2 mile S62° W of Harpers Tavern	x	.....	.....	.....	10
10. Two quarries and bluff along Swatara Creek 0.8 mile S29° W of Ono	.....	x	.....	.....	60
11. Roadcut 1.5 miles S79° E of Snyder	x	.....	.....	.....	50
12. Quarry 1.6 miles S66° E of Snyder	.....	.....	x?	.....	100
LEBANON QUADRANGLE					
13. Railroad cut 1 mile N82° W of Coheva	.....	x?	.....	x?	105 270
14. Quarry 0.3 mile S11° E of Jonestown	.....	.....	x	.....	50
15. Ledges along road 1 mile S9° W of Johnestown	.....	.....	x	.....	15
16. Exposure along road 0.4 mile S8° W of Fredericksburg	.....	x	.....	.....	1
17. Roadcut 0.5 mile east of Greble bridge	.....	x	.....	.....	8

TABLE 1.—*Limestone exposures in the shale belt (western region)*—continued

Locality*	Martinsburg	Probably Martinsburg	Beekmantown	Leesport	Thickness (feet)
WERNERSVILLE QUADRANGLE					
18. Quarry along Irish Creek 0.8 mile S63°W of Centerport	.....	x	.....	.....	35
19. Quarry 1.7 miles S88° E of Obold	.....	x	.....	.....	35
20. Bluff along road 0.65 mile S46°E of Obold	x	.....	.....	.....	4
21. Large quarry 0.9 mile S46° E of Obold	.....	x	.....	.....	50
22. Quarry 1 mile S44° E of Obold	.....	x	.....	.....	12
23. Area 1 mile east-west and 0.2 mile north-south, including Hiesters Mill in southwest corner	.....	.....	x	x	?
24. Two quarries 1.3 miles N81° E of North Heidelberg	.....	x	.....	.....	75
25. Quarry 0.4 mile N27° W of Obold	.....	x	.....	.....	47
26. Quarry in field 1.6 miles S82° W of Obold	.....	x	.....	.....	25
27. Quarry 0.2 mile S20° E of Host	.....	.....	x?	.....	50?
28. Quarry 0.3 mile N54° W of Host	.....	.....	x?	.....	80
READING QUADRANGLE					
29. Three small quarries 0.5 mile N80° W of Gernant Church	.....	.....	x?	.....	20
30. Roadcut 0.35 mile S35° E of Mohrsville, showing several zones of limestone	x	.....	.....	.....	35
31. Roadcut 1.4 miles N64° W of Mohrsville	x	.....	.....	.....	3
32. Bluff along Irish Creek 1 mile N77° W of Mohrsville	.....	x?	.....	x?	20
33. Quarry 0.4 mile N33° W of Dauberville	.....	x	.....	.....	66
34. Type section of Leesport formation in cut of Reading Railroad at West Leesport Station. Upper 64 feet considered possibly Martinsburg	.....	x?	.....	x?	64
35. Large shale quarry 0.5 mile S12° W of Hecktown School	x	.....	.....	.....	1
HAMBURG QUADRANGLE					
36. Crystal Cave 1.7 miles N90° E of Virginville	.....	x	.....	.....	100
37. Quarry 0.95 mile N80° E of Virginville	.....	x	.....	.....	10
38. Onyx Cave 1.7 miles S72° W of Virginville	.....	x	.....	.....	100
39. Roadcut and quarry 1.2 miles S42° W of Virginville	.....	x	.....	.....	50
40. Roadcut 0.4 mile N80° E of Klineville	x	.....	.....	.....	4
41. Roadcut 1.2 miles N85° E of Klineville	x	.....	.....	.....	15
42. Ledges on hillside 1.4 miles S59° W of Virginville	.....	x	.....	.....	15

* Numbers correspond with those used in Figure 2.

for including scores of feet of homogeneous shale in the Leesport, and he believes that if limestone is present in these areas it should be considered interbedded within the Martinsburg formation. However, if the Leesport does contain considerable quantities of interbedded shale, as Stose and Jonas believe, it would be justifiable to map an area somewhat larger than the exposures of the limestone.

LIMESTONE AREAS IN THE SHALE BELT (EASTERN REGION)

Exposures of limestone east of the Lehigh River are found in the lower member of the Martinsburg near Howertown and Seemsville, in the northwest part of the Allentown quadrangle (Fig. 3). These limestones differ from those in the western region; the former are massive-bedded, partly dolomitic and have few shaly partings or shale layers between the limestone beds. Behre [21] reported *Cryptozoon* in this limestone at several different localities. The best exposure of *Cryptozoon*, found by the author, is in a small abandoned quarry along a woods lane 0.9 mile S34°E of Seemsville (Fig. 3, no. 2). Miller [22] and Behre [23] have mapped these eastern limestone areas; both have interpreted them as interbedded limestones in the Martinsburg, although Behre,[24] in his later slate report, suggests that they may be Cambrian limestones in unconformable or fault relation to the shale. Stose and Jonas [25] had suggested this interpretation previously.

Two lines of evidence favor an Upper Cambrian age for these limestone areas. (1) There is a lithologic similarity to the known Upper Cambrian beds of the region. (2) In a number of different exposures, the fossil *Cryptozoon*, which elsewhere in the valley is restricted to the Upper Cambrian, has been found.

The evidence, which opposes an Upper Cambrian age and favors a Martinsburg designation for these limestones, has not been presented in the literature, although both Behre and Miller were aware of it when they mapped the limestones as Martinsburg.[26] Everywhere along this part of the Lehigh Valley, 600 feet of Jacksonburg and 1200 feet of Beekmantown limestone intervene between the Martinsburg shales and the Upper Cambrian. Within the shale belt, however, the Jacksonburg and the Beekmantown are nowhere exposed. In a quarry, 1 mile

[21] C. H. Behre, Jr.: *Slate in Pennsylvania*, Pa. Geol. Surv., Bull. M 16 (1933) p. 136.

[22] B. L. Miller: *Mineral resources of the Allentown quadrangle, Pennsylvania*, Pa. Geol. Surv., Topog. and Geol. Atlas, no. 206 (1925) p. 130.

[23] C. H. Behre, Jr.: *Slate in Northampton County, Pennsylvania*, Pa. Geol. Surv., Bull. M9 (1927) p. 21-23.

[24] C. H. Behre, Jr.: *Slate in Pennsylvania*, Pa. Geol. Surv., Bull. M 16 (1933) p. 135-136.

[25] G. W. Stose and A. I. Jonas: *Ordovician shales and associated lava in southeastern Pennsylvania*, Geol. Soc. Am., Bull., vol. 38 (1927) p. 513.

[26] Despite Behre's consideration of a possible Upper Cambrian age for these limestones in his 1933 Slate Report, they still appear as Martinsburg on the maps of that bulletin.

S70°E of Seemsville (Fig. 3, no. 9), 40 feet of gently dipping, massive, dolomitic limestone is overlain by 5 feet of thin limestone beds with shaly partings; above this is another massive bed 4 feet thick, topped by shale, all in apparent conformity. The transition from massive beds to platy limestone with shaly partings, to shale, is common in the western region, where the Martinsburg equivalence of the limestones is demonstrable, and favors that interpretation here. Behre [27] reports *Cryptozoon* from this quarry, but the author was unable to find any. If the limestone be considered Upper Cambrian on the basis of *Cryptozoon* and the lithology, the absence of 1800 feet of intervening Jacksonburg and Beekmantown beds must be explained. The nature of the contact in the quarry described seems to preclude the possibility of faulting or of great unconformity at this locality.

The limestone exposures in the shale belt are so similar to each other and so closely grouped that there seems no reason to doubt that they have a common explanation. The quarry cited is the only exposure in which actual contact of the limestone with the shales is seen. There are, however, two general reasons for believing that faulting or unconformity cannot apply any better to the other limestone areas where the marginal relations are concealed.

(1) One small limestone exposure, located along Catasauqua Creek 0.9 mile N70°E of Howertown (Fig. 3, no. 7), lies only 200 yards north of the southern margin of the shale belt. Several others are but little farther away. If unconformity be postulated, it would require that 600 feet of Jacksonburg and 1200 feet of Beekmantown thin out, either by non-deposition or by subsequent erosion, in a horizontal distance of 600 feet. This seems impossible.

(2) If faulting be invoked, it would be very difficult to devise any scheme of faults that would bring at least six small blocks of Upper Cambrian into the observed relations with the shales. When one considers that this must happen at six places without leaving at the surface any of the intervening 600 feet of very distinctive Jacksonburg limestone, or the 1200 feet of less distinctive Beekmantown limestone, the difficulties involved in a fault interpretation become great.

The field relations point strongly to a Martinsburg equivalence for the limestone areas in the shale belt. They are interpreted as limestone lenses deposited in local areas of the dominantly muddy Martinsburg sea. In this connection, it should be mentioned that parts of the middle or sandy member of the Martinsburg are notably calcareous in this region, and fresh specimens will effervesce freely with dilute acid. If the limestones are a part of the lower Martinsburg, the genus *Cryptozoon*

[27] Personal communication.

would be at a Trenton horizon. A review of the literature on *Cryptozoon* reveals that Sir William Dawson [28] described a species of this genus, which he named *Cryptozoon boreale,* associated with Trenton fossils at Lake St. John, Quebec. However, the specimens under discussion are not *Cryptozoon boreale.* They more closely resemble *Cryptozoon proliferum,* although the canaliculi cannot be seen, perhaps because of the

TABLE 2.—*Limestone exposures in the eastern region (Allentown quadrangle)*

Locality	Thickness (feet)
1. Abandoned quarry 0.75 mile N67°W of Jacksonville. No bedrock exposed	?
2. Quarry along woods lane 0.9 mile S34°E of Seemsville	25
3. Quarry 0.95 mile S35°E of Seemsville. Same beds as 2	15
4. Roadcut 0.9 mile S26°E of Seemsville	10
5. Quarry 1.2 miles S27°E of Seemsville	10
6. Quarry along road 1.15 miles S19°E of Seemsville	29
7. Bank along Catasauqua Creek 0.9 mile N70°E of Howertown	6
8. Quarry 0.8 mile N48°E of Howertown	20
9. Quarry 1 mile S70°E of Seemsville	50
10. Quarry 0.9 mile N88°E of Seemsville. No bedrock exposed	?
11. Quarry 0.85 mile N77°E of Seemsville	25

crystallinity of the limestone. They are smaller, however, than the *Cryptozoon* cf. *C. proliferum* found in the Upper Cambrian limestone of the Lehigh Valley. The difficulties involved in assigning an Upper Cambrian age to those limestones within the shale belt which contain *Cryptozoon* seem so formidable that the author believes it is more logical to extend the range of *Cryptozoon* cf. *C. proliferum* to the Trenton. It has been noted that *Cryptozoon*-like fossils are reported from beds of Trenton age.[29]

In maintaining the Martinsburg equivalence of the limestones within the shale belt in the eastern region, structural evidence has been favored over lithologic similarity. In the western region, lithologic dissimilarity to the Leesport limestone has been advanced as an argument supporting the other lines of evidence favoring a Martinsburg equivalence. It should be pointed out that, in the western region, the argument set forth was that the limestones in the shale belt are lithologically very much alike, but

[28] Sir William Dawson: *Note on Cryptozoon and other ancient fossils,* Canad. Rec. Sci., vol. 7 (1896) p. 203-217.

[29] H. M. Seely [*Report of the Vermont State Geologist,* 1905-1906, p. 169] suggests that Dawson's *Cryptozoon boreale* perhaps may be more correctly referred to some other genus because of its high position in the Ordovician.

they are very different from the Leesport limestone. Inasmuch as many of the limestone areas were proved to be Martinsburg on other grounds, it is logical to believe that, where contradictory evidence is absent, they are all Martinsburg. In the eastern region, the argument was that the limestones within the shale belt are lithologically very much alike, and they are also very similar to the Upper Cambrian. However, one of the *Cryptozoon*-bearing areas is evidently Martinsburg. Inasmuch as there are strong objections to an Upper Cambrian age for the others, it is more logical to conclude that they are the same as the known Martinsburg limestones which they resemble lithologically than to believe that they are Upper Cambrian limestone, which they also resemble.

Table 2 indicates the locations of the eleven known Martinsburg limestone exposures in the eastern region. The numbers correspond to those on the map (Fig. 3). Distances and bearings are scaled from the topographic map of the Allentown quadrangle, 1893 edition. Thicknesses given are for the limestone exposed and are not maxima.

GENERAL SUMMARY AND CONCLUSIONS

The limestones which crop out in the Martinsburg shale belt in the Lehigh and the Lebanon valleys are usually interbedded within the Martinsburg formation. At some localities, exposures of the base and of the top of the limestone show vertical gradation by intercalation into homogeneous shales. In most of the limestone areas where marginal relations are not exposed, lithologic and structural evidence indicate similar relations. Inasmuch as one anticlinal Leesport and four anticlinal Beekmantown areas are recognized, each limestone area must be studied individually.

The Martinsburg limestones are lenticular, of restricted extent, and are found at different horizons. In general, they are most abundant in the lower part of the formation. Limestone areas in the northern part of the shale belt may represent reappearances of the lower part of the formation by anticlinal uplift, as Stose has interpreted along the Susquehanna River. It has not been possible to determine on similarity of lithology and thickness if limestone exposures lying several miles apart across the strike are repetitions of the same limestone beds. Such similarity is suggestive but not conclusive. In the eastern region, limestones are present in the lower member of the Martinsburg and seem absent in the upper member (of Behre), suggesting that the latter is not the lower member repeated by folding, as proposed by Stose. Further study is needed to clarify the unsettled problems of structure and stratigraphy of the Martinsburg formation in Pennsylvania.

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PETROGRAPHIC ANALYSIS OF THE GLENWOOD BEDS OF SOUTHEASTERN MINNESOTA

BY GEORGE A. THIEL

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INTRODUCTION

In a recent paper [1] on the petrographic characteristics of the St. Peter sandstone, the writer pointed out that in the upper Mississippi Valley, the petrographic constituents of the upper portion of the St. Peter are more typical of the Glenwood beds than of the major portion of the St. Peter sandstone. Throughout the area of outcrop of the sandstone in southeastern Minnesota and northeastern Iowa, the upper 3-10 feet of the formation is thin-bedded, more poorly sorted, and consists of coarser sand and more fine silt and clay than the greater part of the formation. Further studies of numerous samples from widely separated outcrops of the Glenwood beds and underlying clayey sandstone layers indicate that the early Mohawkian sea reworked the upper part of the St. Peter sands in the upper Mississippi Valley, and that additional clastic sediments from new source areas, differing both texturally and petrographically from the St. Peter, were also being transported to the basin where they were mixed with the sands derived from the St. Peter. The sandstone formed from this admixture is an early phase of Glenwood deposition and should be classified as such.

ACKNOWLEDGMENTS

The writer wishes to acknowledge with gratitude the able assistance given by Mr. Gilman Berg in the collection of samples and in the measur-

[1] A sequel to the paper by G. A. Thiel: *Sedimentary and petrographic analysis of the St. Peter sandstone*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 559-614.

ing of sections in the field. Mr. Samuel Goldich and Mr. Robert Grogan assisted in the laboratory work; the X-ray analyses were made by Dr.

TABLE 1.—*Stratigraphic relations of the Glenwood beds in the upper Mississippi Valley*

		Minnesota	Iowa*	Illinois† (west-central)	Missouri‡
Mohawkian	Trenton	Galena Stewartville Prosser	Galena Dubuque Stewartville Prosser	Galena	Kimmswick
		Decorah	Decorah Ion Guttenberg	Decorah	Decorah
	Black River	Platteville Spechts Ferry McGregor Glenwood	Platteville Spechts Ferry McGregor Pecatonica Glenwood	Platteville	Plattin Upper Joachim
Chazyan		St. Peter	St. Peter	Glenwood St. Peter	Lower Joachim St. Peter

* G. Marshall Kay: *op. cit.*

† L. E. Workman: *Mississippi Valley geologic cross-section,* Kansas Geol. Soc., 9th Ann. Field Conf. Guidebook (1935) p. 362.

‡ F. C. Edson: *A résumé of St. Peter stratigraphy,* Bull. Am. Assoc. Petr. Geol., vol. 19 (1935) p. 1110.

J. W. Gruner. Financial support for laboratory assistance was supplied by the Research Fund of the Graduate School, University of Minnesota.

STRATIGRAPHIC RELATIONS

Nearly all exposures of the upper part of the St. Peter sandstone consist of thin beds of bluish-green or olive-green shale of variable thickness between the white massive sandstone and the overlying Platteville limestone. In northern Iowa and southern Minnesota, the shale beds range in thickness from 10 feet to the vanishing point, but they thicken considerably toward the south, and are nearly 100 feet thick at DeKalb, Illinois. Wherever the beds are present, they lie on the St. Peter sandstone. However, the same member of the Platteville formation is not found everywhere overlying the shales. In Illinois, Wisconsin, and Iowa, the Glenwood beds are succeeded by the Pecatonica member of the Platte-

ville,[2] whereas, over most of southern Minnesota, the Pecatonica member is missing, and the Glenwood beds are succeeded by the McGregor member of the Platteville (Table 1).

Kay [3] states that "the reported fauna of the Glenwood is limited to a number of species of conodonts from exposures in southern Minnesota and northern Iowa." He refers to Stauffer's [4] paper on the conodonts of the Glenwood beds as the basis for the above quotation. However, in the paper to which Kay refers, Stauffer does not limit the fauna to conodonts, but states that megascopic forms have long been known from the Glenwood of southeastern Minnesota. He lists the following genera:

Climacograptus	*Rafinesquina*
Vinella	*Rhynchotrema*
Lingula	*Strophomena*
Orthis	*Lophospira*
Pianodema	*Conularia*
Platystrophia	*Pterygometopus*

Some of the above genera are represented by several species and indicate a Platteville age. Many of the most characteristic middle Ordovician forms have been found in the same bed with minute conodont fossils. The conodonts are, in many instances, similar to those found in the Decorah shale that overlies the Platteville.

Branson and Mehl [5] have isolated a mixed conodont fauna from the Glenwood. Some forms are similar to those found in the Harding sandstone in Colorado; others are typically Plattin. As the Harding and the Plattin are generally considered to be the equivalents of the St. Peter and the Platteville respectively, the Glenwood could be assigned no definite stratigraphic position. However, Stauffer [6] has pointed out that the typical Harding conodonts found in the Glenwood have a tough, fibrous structure, and may represent residual fossils from the reworked upper part of the Harding or St. Peter sands. He believes that some of the land area and the derived fossils may have been of St. Peter age, but the Glenwood sea was inhabited by Mohawkian life, and most of its fauna is of that age.

METHODS OF STUDY

Outcrops of the Glenwood beds were sampled with special reference to layers with petrographic variations. In some cases, an individual sample

[2] G. Marshall Kay: *Ordovician system in the Upper Mississippi Valley*, Kansas Geol. Soc., 9th Ann. Field Conf. Guidebook (1935) p. 281.
[3] *Op. cit.*
[4] C. R. Stauffer: *Conodonts of the Glenwood beds*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 125-168.
[5] E. B. Branson and M. G. Mehl: *Conodont studies no. 2*, Univ. Mo. Stud., vol. 8 (1933) p. 19-38.
[6] C. R. Stauffer: *op. cit.*, p. 130.

represented a layer no more than an inch in thickness (Table 4). Only freshly exposed sections were sampled. As the bottom of the Platteville limestone is a more definite horizon than the bottom of the Glenwood beds,

TABLE 2.—*Percentage by weight of representative samples retained after washing and percentage by weight of heavy minerals in the washed residue*

Sample no.	Per cent of original sample retained	Per cent of heavy minerals
C 1	24.0	0.3
C 3	42.2	0.1
C 5	77.2	0.2
C 8	42.4	1.4
C 9	77.1	0.5
F 4	44.0	0.8
F 5	73.4	0.6
F 6	43.6	0.7
F 7	79.1	2.4
P 3	34.7	0.3
SG 3	42.1	1.1
W 4	22.5	0.1
W 5	47.2	0.4

the samples were numbered from the top downward (Table 4). Each measured section included from 5 to 20 feet of the white sandstone at the top of the St. Peter sandstone.

As the major purpose of the investigation was to determine the stratigraphic position of the top of the St. Peter sandstone, the chief method of study was to compare the accessory minerals of the Glenwood beds with those of the St. Peter. For this purpose, only the coarser fractions of the Glenwood beds were required. To eliminate the fine clayey material, all of the shaly samples were crushed, and slaked for several hours in a solution of sodium carbonate. The samples that did not slake readily were placed in bottles containing the sodium carbonate solution and were shaken for two hours in a shaking machine. The bottles were then allowed to stand for two and a half minutes, after which the sediment still in suspension was siphoned off and discarded. In a few samples, the fine clay in suspension was recovered and used for X-ray analyses.

The sediments that settled in the bottles were washed, dried, and subjected to bromoform separation. The samples that contained an appreciable amount of iron oxide were digested in a hot solution of hydrochloric acid and stannous chloride before a bromoform separation was made. Many of the samples from sandstone layers interbedded with the shales contained so many conodont fragments in the heavy fractions that the

fossil fragments interfered with the counting of heavy mineral grains. In order to eliminate the fossils, all the heavy mineral fractions were treated with hydrochloric acid before they were mounted in balsam for counting.

The percentage distribution of heavy minerals was determined by identifying and counting from 300 to 500 mineral grains from each sample.

TEXTURAL AND MINERALOGIC COMPOSITION

The Glenwood beds vary in texture from coarse sandstone to finely laminated shales. The amount of sand and silt in the shale beds is indicated by the percentage of the sample retained after the "fines" were

TABLE 3.—*Textural characteristics of sandstone layers in and at the base of Glenwood beds compared with St. Peter sandstone of Minnesota*

	Number of samples	Median diameter in millimeters	Coefficient of sorting	Coefficient of skewness
Glenwood	31	.334	1.59	.94
St. Peter	72	.213	1.42	1.03

washed out and decanted (Table 2). The basal sandy beds are composed, for the most part, of sands very similar to those of the St. Peter, but, in addition, they contain a small percentage of the accessory minerals that characterize the sandstone layers interbedded with the shales. In all the sections that were sampled, a layer from 1 to 3 feet in thickness, composed of a mixture of coarse sand in a fine white to pale-green, clayey matrix, is found several feet above the base of the Glenwood (Sample M 5, Table 4). This sand is much coarser grained than is the St. Peter, and it contains an entirely different assemblage of accessory minerals. The mixture of coarse sand and fine clay grades upward into pale-green shale, which contains varying amounts of quartz. The green color is undoubtedly due to the presence of a small amount of fine-grained glauconite.

Sardeson[7] refers to this shaly sandstone as bentonitic sand. He believes that a fall of volcanic ash interrupted the deposition of reworked St. Peter sand. However, an X-ray analysis of the clay does not show the patterns of such clay minerals as montmorillonite and leverrierite that are characteristic of bentonite. The X-ray patterns correspond with the pattern obtained from orthoclase feldspar.[8] A partial chemical analysis

[7] F. W. Sardeson: *Stratigraphic affinities of Glenwood shales*, Pan-Am. Geol., vol. 60 (1933) p. 81.
[8] Further X-ray studies have been made by Dr. J. W. Gruner. The results are in press.

TABLE 4.—*Sections of the Glenwood beds showing lithological characteristics and percentage distribution of heavy minerals based on number of grains present*

Geographic and Stratigraphic Location of Samples	Lithology	Thickness (inches)	Percentage Distribution of Heavy Minerals									
			Garnet	Zircon	Tourmaline	Epidote	Leucoxene	Magnetite & Ilmenite	Hornblende	Rutile	Unknown	Miscellaneous*
MINNEAPOLIS, MINN.												
Top–M1	Shale, calcareous	14	31	30	15	3	3	7	....	....	3	Chl 7, Tm 1
M2	Shale, grayish-green	4	4	22	11	Pr	2	2	....	....	Tr	Py 58
M3	Clay, black, sticky	2	65	27	4	....	2	Tr	....	....	....	Py 1, Sp-Tr
M4	Shale, pale-green, sandy	18	44	12	16	....	Pr	Tr	....	....	....	Py 27
M5	Sandstone, buff to white, clayey	20	35	38	22	....	2	Tr	....	....	Pr	Py 2
M6	Sandstone, ferruginous	12	31	46	18	....	4	1	....	Tr	....	An-Tr
M7	Sandstone, banded, ferruginous	30	5	61	30	....	3	Tr	....	Tr	Tr	An-Tr
M8	Sandstone, white,—distinct bed	12	Tr	79	15	Tr	4	....	....	....	Pr	
M9	Sandstone, pale-green	5	Tr	78	18	....	3	....	....	....	Pr	
M10	Sandstone, white—‡St. P.	24	....	40	28	....	31	....	....	....	Tr	
FOUNTAIN, MINN.												
Top–F1	Limestone, (basal Platteville)	120†	....	....	....	....	....	....	....	....	....	
F2	Sandstone, cross-bedded	60	40	26	16	6	4	2	2	3	....	Cor 1
F3	Shale, dark-gray	1	32	32	9	1	8	10	1	1	2	Tm 2
F4	Shale, green, sandy	5	37	42	11	....	3	2	....	4	1	
F5	Sandstone, brown, shaly	2	26	47	13	....	6	....	Pr	4	3	
F6	Shale, green	24	28	30	20	2	4	6	1	3	2	Tm 1, Zo 2
F7	Shale, green, sandy	3	5	57	17	Tr	5	....	Tr	14	2	
F8	Shale, green	6†	....	....	....	....	....	....	....	....	....	
F9	Sandstone, brown and green, shaly	8	1	60	22	4	3	1	1	6	4	Chl 1
F10	Sandstone, white	60	Tr	74	21	....	3	....	....	Pr	1	An-Tr
F11	Sandstone, white—‡St. P.	12	....	52	37	....	9	....	....	....	2	
F12	Sandstone, white—‡St. P.	96	....	63	28	2	6	....	....	....	Tr	
CHATFIELD, MINN.												
Top–C1	Shale, green	6	17	7	3	19	7	....	20	22	2	Py 3
C2	Shale, brown, sandy	4	72	15	13	Tr	Tr	Tr	Tr	....	Tr	
C3	Shale, green	7	58	19	18	Pr	Pr	....	Pr	2	....	Py 1
C4	Sandstone, cross-bedded, ferruginous	16	75	17	5	....	1	1	Pr	....	....	
C5	Sandstone, brownish-green, shaly	12	18	38	22	4	5	Pr	3	8	2	
C6	Shale, green	8†	....	....	....	....	....	....	....	....	....	
C7	Shale, mottled, dark-green	5	19	37	21	2	1	1	1	7	....	Py 10
C8	Shale, dark-brown	6	14	39	18	2	2	1	9	3	7	Py 5
C9	Sandstone, shaly	16	2	56	34	....	4	Tr	....	1	3	
C10	Sandstone, pale-green and yellow	60	1	63	31	Pr	2	Tr	....	....	2	
C11	Sandstone, white—‡St. P.	132	....	63	33	....	1	1	....	....	2	
WAUKON, IOWA												
Top–W1	Limestone, buff (basal Platteville)	....	....	....	....	....	....	....	....	....	....	
W2	Shale, brown	28	51	26	9	....	6	....	....	8	....	
W3	Shale, dark-green	6	26	21	13	3	4	4	11	7	3	An-3, Chl-3 Tm-1
W4	Shale, light-green	30	16	63	14	....	3	....	2	....	2	
W5	Shale, gray-green, sandy	6	Pr	83	8	3	2	1	Tr	Tr	2	
W6	Sandstone, ferruginous, shaly	6	3	62	21	2	11	....	Pr	....	....	
W7	Sandstone, ferruginous	4	1	75	13	Pr	7	Pr	1	....	....	Tm-1
W8	Sandstone, white, clayey	3	Tr	58	23	2	12	1	....	....	3	
W9	Sandstone, ferruginous, yellow	14	Pr	64	18	Tr	16	....	....	....	Tr	
W10	Sandstone, white	60+	....	67	26	2	4	....	Pr	....	....	Tm-Tr
PRESTON, MINN.												
Top–P1	Shale, green	18	41	34	17	....	2	1	....	4	1	
P2	Shale, bright-green	2†	....	....	....	....	....	....	....	....	....	
P3	Sandstone, greenish, shaly	8	14	45	19	10	3	2	3	Tr	3	
P4	Sandstone, greenish-white, shaly	3†	....	....	....	....	....	....	....	....	....	
P5	Sandstone, ferruginous	18†	....	....	....	....	....	....	....	....	....	
	Talus	36†	....	....	....	....	....	....	....	....	....	
P6	Sandstone, ferruginous	48	2	78	8	Tr	11	....	....	....	Tr	
P7	Sandstone, white, friable	60+	....	63	22	2	9	2	....	1	....	
SPRING GROVE, MINN.												
Top–SG1	Limestone, buff (basal Platteville)	....	....	....	....	....	....	....	....	....	....	
SG2	Shale, green	14	6	35	15	6	5	5	7	4	7	Bi-Pr, Fl-4 Tm-3, Py-Pr, Zo-2
SG3	Shale, light-green	10	5	40	25	Pr	22	2	Pr	2	2	Zo-1
SG4	Sandstone, mottled, shaly	8†	....	....	....	....	....	....	....	....	....	
SG5	Shale, green	3	....	54	28	3	12	....	Pr	2	....	Cor-1
SG6	Sandstone, hard, shaly	5†	....	....	....	....	....	....	....	....	....	
SG7	Sandstone, mottled, reddish	12†	....	....	....	....	....	....	....	....	....	
SG8	Sandstone, buff	60†	....	....	....	....	....	....	....	....	....	

*An—Anatase Chl—Chlorite Fl—Fluorite Py—Pyrite Tm—Tremolite Bi—Biotite Cor—Corundum
Mu—Muscovite Sp—Sphene Zo—Zoisite Pr—Present, 0.5%—1% Tr—Trace, less than 0.5%
†Heavy minerals not counted. ‡St. P.—St. Peter sandstone.

TABLE 4.—*Sections of the Glenwood beds (continued)*

Geographic and Stratigraphic Location of Samples	Lithology	Thickness (inches)	Percentage Distribution of Heavy Minerals									
			Garnet	Zircon	Tourmaline	Epidote	Leucoxene	Magnetite & Ilmenite	Hornblende	Rutile	Unknown	Miscellaneous*
ROCHESTER, MINN.												
Top–R1	Shale, ferruginous	6	27	13	2	14	7	19	8	Pr	2	Zo-7 Fl-Pr, Mu-Pr, Zo-Pr
R2	Shale, green, sandy	18	17	48	15	2	5	2	1	2	6	
R3	Sandstone, ferruginous, shaly	6	2	65	27	Tr	6	.....	.....	Tr	....	
R4	Sandstone, buff	48†	.....	.....	.....	.....	.....	.....	.....	.....	.....	
R5	Sandstone, white	60+	Tr	54	23	Tr	12	Pr	....	9	1	

of the fraction finer than $\frac{1}{16}$ millimeter in diameter yielded K_2O 6.5% and Na_2O 0.45%.[9] A microscopic examination of the fine material showed, in the order of their abundance, light-colored, finely crystalline, and earthy aggregates, orthoclase, and quartz. The orthoclase is in irregular grains and small euhedral crystals, 0.04 millimeter or less in diameter. The coarse sands of this "bentonitic" horizon differ both texturally and mineralogically from the St. Peter. This marked change in petrographic constituents suggests a change in the source areas of the sediments.

In many localities, sandstone strata are interbedded with the Glenwood shales (Table 4). A summary of their textural characteristics is given in Table 3.

HEAVY MINERAL ACCESSORIES

Garnet, zircon, and tourmaline are the most abundant minerals in the heavy fractions (Table 4). Locally, rutile and other titanium-bearing minerals are abundant. Some of the rutile is nearly opaque and therefore may have been counted as ilmenite. There are a few grains of epidote, zoisite, hornblende, chlorite, fluorite, biotite, muscovite, tremolite, ceylonite, anatase, sphene, staurolite, and corundum. Several samples contained abundant pyrite, and a few showed floods of limonite and hematite. Because of their secondary nature, these iron oxides were either removed or ignored in the counting of the detrital grains.

The distribution of garnet is approximately the same in all the sections (Table 4). It is very abundant in the upper third of the Glenwood, and decreases until it is absent toward the base. The mineral is exceedingly rare in the typical St. Peter sandstone; it was found in only two of 103 samples.[10] This decrease in garnet toward the base of the Glenwood is accompanied by an increase in zircon. In the basal beds, approximately 60 per cent of the heavy accessory grains are zircon.

Tourmaline is relatively uniform in its distribution; it is present in

[9] R. B. Ellestad, Rock Analysis Laboratory, University of Minnesota, analyst.

[10] G. A. Thiel: *Sedimentary and petrographic analysis of the St. Peter sandstone*, Geol. Soc. Am., Bull., vol. 46 (1935) p. 594.

all the samples that were studied. In the Glenwood section at Minneapolis, it makes up about 17 per cent of the heavy mineral assemblage.

The distinct difference between the heavy mineral distribution in the Glenwood and in the St. Peter may be seen by comparing Table 5 with Table 4.

CONCLUSIONS

The data presented in the tabulations are considered sufficient to justify the following conclusions:

(1) The Glenwood sea was of post-Chazyan age. Both the microfauna and the megascopic forms indicate that the Glenwood beds represent a basal phase of the Platteville formation. No structural or faunal break separates the Glenwood from the Platteville, whereas a corrosion zone and a definite petrographic change mark the boundary between the Glenwood and the St. Peter.

TABLE 5.—*Percentage distribution of heavy minerals 20 feet below the top of the St. Peter formation, based on the number of grains* *

Geographic location	Zircon	Tourmaline	Leucoxene	Rutile
N. Minneapolis	53	19	17	8
Mounds Park	41	7	51	
Mendota	38	6	52	3
Chimney Rock	65	26	6	2
Rochester	60	24	13	
Chatfield	35	45	20	
Caledonia	80	8	12	
Decorah (Iowa)	71	29		

* G. A. Thiel: *op. cit.*, p. 596, table 13.

(2) The upper 5-10 feet of what is now called St. Peter sandstone in Minnesota and northeastern Iowa represents St. Peter sands that were reworked by the early Mohawkian sea. The coarser texture of the sand and the presence of a small percentage of garnet in the heavy accessories suggest that other clastic sediments were also being added from new source areas. This mixture is an early phase of the Glenwood beds and should not be termed upper St. Peter. Samples M7, M8, and M9 (Table

4) represent the basal sandstone of the Glenwood in the Minneapolis section. Samples F9 and F10 and C9 and C10 (Table 4) are from the basal beds of the Fountain and Chatfield sections. Similar sandstone beds are present between the typical St. Peter sands and the Glenwood shales in numerous other sections. The top of the St. Peter is represented by samples M10, F11, C11, W10 and P7 of Table 4.

(3) The question may be raised as to whether the difference between no garnet (M10, F11, C11, W10) and a trace of garnet (M9, F10, C10, W9) is more significant than the difference between 5 per cent and 12 per cent garnet (M9 and M8), 12 per cent and 30 per cent garnet (M8 and M7), or 2 per cent and 14 per cent garnet (C9 and C8). The writer believes that a trace of garnet is more significant than the difference in the percentage of garnet present. The typical St. Peter of Minnesota has scarcely a trace of garnet. In the clayey sandstone beds of the basal Glenwood, garnet is present in every sample that was studied. Once garnet makes its appearance, there is no break. The new source areas supplied progressively more and more of the sediment for the Glenwood beds.

(4) As Mohawkian time progressed, clayey sediments became more abundant. Some coarse sands were mixed with the clay, and the mixture formed the sandy shales that overlie the basal sandstones of the Glenwood; very little of this material was derived from the St. Peter. The heavy mineral assemblage is distinctly different from that of the St. Peter sandstone. This horizon is represented by samples M5, M6, F5, F6, and F7, C9, W5, and W6, in the sections of Table 4.

(5) The shale layers in the Glenwood beds show approximately the same ratio of minerals in their heavy fractions as do the sandstones interbedded with the shales. The so-called bentonitic clays, which are mainly recrystallized to orthoclase, contain well-rounded detrital grains of garnet, zircon, and tourmaline. The presence of these detrital minerals does not favor the volcanic origin of the shale, X-ray analyses also fail to demonstrate the presence of bentonitic clay minerals, and chemical analyses show a higher percentage of potash than is common in the average volcanic rock.

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MIN RIVER SECTION BETWEEN KUAN-HSIEN AND WEI-CHOU, SZECHUAN, CHINA

BY GEORGE DAVID HUBBARD

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INTRODUCTION

SITUATION

The Min River flows in the eastern borders of the great mountain-plateau mass of central Asia; at Kuan-hsien, it emerges upon the Plain of Chengtu to make its way easily across the Red Basin of Szechuan to the Yangtse at Suifu. The area covered by this report, latitude 30° 55′ to 31°

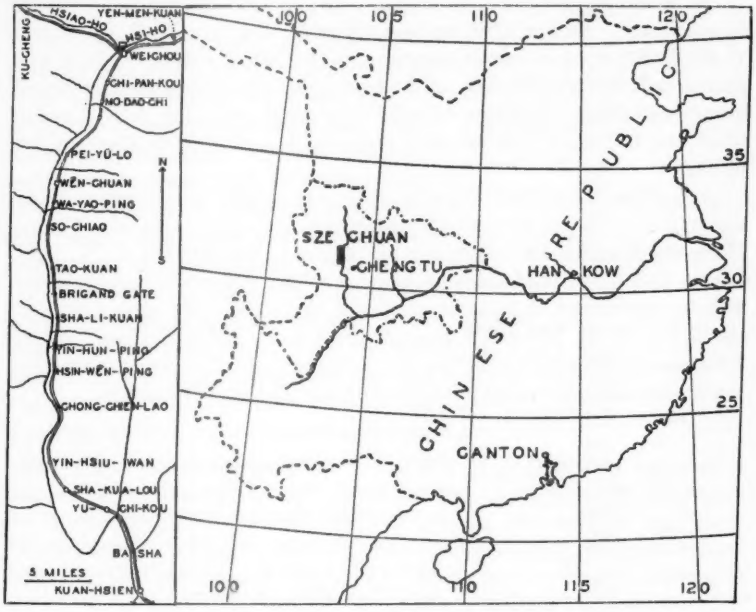

FIGURE 1.—*Szechuan and the Min River area*

32′ North, and longitude 103° 18′ to 103° 34′ East, lies along the river, beginning at Kuan-hsien, nearly 40 miles northwest of Chengtu, capital of the province of Szechuan, and extending 40 miles northward to Wei-chou, where the Hsiao Ho enters the Min from the west (Fig. 1).

This is a deep, youthful valley with steep, rocky slopes among mountains, which rise to an altitude of more than 8,000 feet, and peaks, 15 miles west of Wei-chou, which attain more than 11,000 feet. The altitude of the valley floor descends from about 4,400 feet at Wei-chou to 2,500 feet at Kuan-hsien, or nearly 50 feet in a mile, producing almost continuous rapids. At a few places in the gorge, small flood plains have developed.

The section lies along the contact of the simple structures of eastern Szechuan and the complex structures of western Szechuan—sedimentary

rocks intruded by many kinds of igneous materials, and extensively metamorphosed. The section studied cuts obliquely across a series of folds with thrust faults whose strike is N54°±E, so nearly parallel with the simple folds of eastern Szechuan as to be correlated with them, although at least a part of the folding and much of the uplift are of later date.

ACKNOWLEDGMENTS

The writer studied the area in some detail in 1921 and collected a suite of specimens. Before a report was prepared, the late Y. T. Chao and T. K. Huang made a reconnaissance trip in 1929, a report of which appeared as Number 9, Series A, of the Geological Memoirs of the Geological Survey of China. Although some of their notes were lost, their descriptions and comments are, in most respects, in accord with those of the writer.

The author hopes that this paper, based upon notes, specimens, and thin sections, may help in the understanding of this portion of the Min Valley. He takes this occasion to register his thanks to the late Dr. V. K. Ting, former director of the Geological Survey of China, for his encouragement and for assistance in locating pertinent literature. He also wishes to thank Dr. W. H. Wong, the present director, for important constructive criticism of this report. To Dr. Fred Foreman, of Oberlin, appreciative thanks are due for careful microscopic study of the thin sections.

GENERAL DESCRIPTION

In many places, through a series of metamorphosed sediments, with some folding and faulting, there has been extensive intrusion, which ranges from light syenites and granites to black basalts. To the developer of mineral products, the valley offers no special attraction, for no rich deposits of metallic ores have been found. Coal, near Kuan-hsien, and so-called jade are the chief rock products.

STRUCTURE

GENERAL STATEMENT

Figure 2 shows the main structures of the valley. Thicknesses are exaggerated because the section lies obliquely across both strike and structure. Strikes range from N 20° E to N 100° E, the average being N 54° E. All except four are within 15 to 16 degrees of this mean. (Magnetic north for this vicinity is shown in surveying treatises to be within one degree of true north; hence, no correction has been made.) Such a narrow range in strike indicates some unity of structure.

The rocks may readily be grouped into 12 series with several subdivisions. Descriptions begin with the southern end of the section, at the wall of Kuan-hsien, on the east side of the stream.

SEDIMENTARY ROCKS

General statement.—A series of sedimentary rocks is crossed in journeying from the city gate of Kuan-hsien to the steep ascent, 2 miles below the Pass of Niang-tsu-ling. For convenience, the series is subdivided into six units.

Conglomerates.—From the city northward for more than a mile is a conglomerate, which strikes N 70° E and dips 70° to 80° SE. Pebbles, rounded and rarely above fist size, range in diameter from 1 foot down to sand, with occasional incorporated slabs of sandstone, 6 to 8 inches thick, and 3 to 4 feet across. Most of the pebbles are from sedimentary rocks; some are vein quartz. No igneous rock was found, a fact indicating that the fragments, which make up the conglomerate, could not have come from the north with its igneous rocks. The conglomerate is obviously younger than the great body of sediments and metamorphics adjacent on the north but is older than many of the igneous rocks now exposed to the north; however, the conglomerate is involved in the folding of these same sediments and metamorphic rocks to the north.

Although the dip changes from southeast to northwest with the rather sharp transition into sandstones and shales, the unconformity, as reported by Chao and Huang,[1] was not seen. The coarse conglomerates seem to thicken and thin within short distances, and to fan out, increasing in thickness downward sufficiently to change the dip.

Sandstones and shales.—For nearly 2 miles, as far as Ba-sha, sandstones and shales succeed the coarser rocks. Dips approaching 90 degrees are common. The

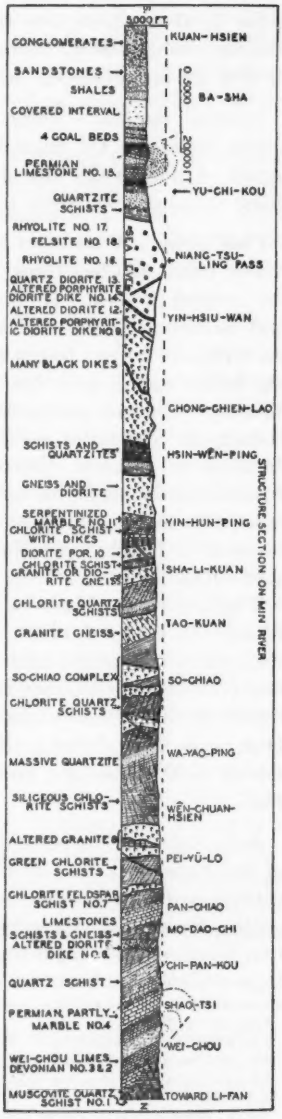

FIGURE 2.—*Structure section*

(S) South, or Kuan-hsien, end of section. Top line on section is 5,000 feet above sea level. Suggested faults are shown in oblique dash lines.

[1] Y. T. Chao and T. K. Huang: *Geology of the Tsinling-shan and Szechuan*, Geol. Surv. China, Mem., ser. A, no. 9 (1931) p. 106-107.

series is about 2,000 feet thick. As a rule, the rocks are not strong, although some beds are 20 to 30 feet thick and some are resistant enough to crop out in ribs far up the young valley wall.

Covered interval.—Talus conceals the bedrock, except high on the slopes, for nearly 1½ miles, but on the west side of the valley, above the mouth of the Ba-sha Ho, the weak layers, visible above the talus, are much jumbled, apparently by local faulting.

Coal series.—A series of bituminous coal beds among sandstones and shales, about 400 feet thick, follows and probably underlies the rocks of the covered interval. Huang[2] reports cycads from among the green and gray sandstones below the coals, and, on this evidence, assigns them to the Suchiaho series. In the culm, and also in beds in place, fossils, including leaves and a probable *Neocalamite* were seen, which suggest late Triassic. Chinese geologists seem to be undecided as to whether this Hsiang-chi coal series should be called Rhaetic, Upper Triassic, Lower Jurassic, or Jurassic. Director Wong says: "These coal series are of Rhaetic age belonging to Lower Jurassic." T'an and Li have found certain plant fossils, *Cladophlebis denticulata* Brongniart and *Podozamites lanceolatus* Lindley and Hutton, which Grabau designates "Upper Lias above Rhaetic."[3]

T'an and Li say, however, that the Hsiang-chi coal series "extends from Rhaetic to Upper Jurassic."[4] In their columnar section of Omeishan, coal seams are interbedded in most of the Jurassic. Heim agrees that this coal series represents the whole Jurassic.[5] C. Y. Hsieh and Y. T. Chiao[6] divide the series into two parts, one being Rhaetic, the other Lias.[7] Dips range from almost vertical to 55° SE; the strikes, probably local, are mostly N 30° to 35° E. Folding repeats much of the sequence, except the coal.

Limestones and associated rocks.—Farther upstream, a long succession of limestones and thin, interbedded shales and sandstones with steep dips extends as far as Yu-chi-kou, the mouth of a torrential stream from the north. Nearly half the series consists of limestones, but cursory examination revealed only fragments of fossils, so that age determination on biologic evidence has been impossible. Position indicates that they are older

[2] *Op. cit.*, p. 107.

[3] A. W. Grabau: *Stratigraphy of China.* Part 2 (1928) p. 147.

[4] H. C. T'an and C. Y. Li: *Geology of Omeishan,* Geol. Surv. China, Bull. 20 (1933) p. 44-45.

[5] Arnold Heim: *The structure of the Sacred Omeishan, Szechuan,* Geol. Soc. China, Bull., vol. 9, no. 1 (1930) p. 68-69.

[6] C. Y. Hsieh and Y. T. Chiao: *Geology of West Hupei,* Geol. Surv. China, Bull. 7 (1925).

[7] F. K. Morris, in a recent letter, writes: "Still more recent studies of Grabau, of several Chinese and Russian scientists, as well as our own, place most of the horizons that bear these fossils in the lower Wealden," which is lower Cretaceous.

than the coal series. Chao and Huang[8] reported the foraminiferan *Schwagerina* of lower Permian age. T'an and Li found the coral *Michelinia siyangensis* Reed, probably of lower Permian, and, a little west of Yu-chi, the foraminiferan *Neoschwagerina* and an undetermined species of *Polythecalis*.

The folded limestone, at least 1,000 feet thick, apparently was thrust from the north upon the younger coal series, although the actual fault plane was not seen. North of these limestones is a section of metamorphosed shales and sandstones, not found to the south. This, and the presence of coals only on the south, suggests a fault on the north side of the limestones also.

A rock sample, taken about half a mile below Yu-chi-kou, showed a dense, firm, even-grained, but distinctly crystalline, dark-gray mass with straw tints on thin edges. Although hundreds of feet thick, this limestone is, for the most part, massive and thick-bedded. It is nearly pure calcium carbonate, with only traces of magnesium, silica, and iron, the latter in tiny pyrite crystals. Clusters of calcite crystals indicate incipient recrystallization; small broken brachiopod shells are embedded in the limestone, and numerous slender calcite veins cross the beds. Veins are smaller, less abundant, and finer in texture than in the corresponding beds upstream on the opposite side of the geanticline. In many beds, regular and nearly cubical jointing yields to a hackly, splintery fracture.

On the southeastern side of the big Yu-chi limestone—the top of it, if the fold interpretation is correct—is a limestone conglomerate or breccia, about 20 feet thick, which is the beginning of the next formation, a thick section of sandstones and shales found on the north side of the folded limestones and partly missing on the south side.

Igneous boulders, particularly granites, quartz porphyries, and trachyte porphyries, make up a much larger proportion of the loose rocks along the stream below Yu-chi-kou than above, a difference suggesting that such boulders were transported by a tributary rather than by the Min itself. Some have a red, felsitic groundmass containing slabs of feldspar, 1 to 2.5 centimeters long and .4 centimeter thick. The possibility that the igneous fragments came from local dikes seems unlikely, for no igneous rocks were seen in place below Yu-chi-kou.

Quartzites and schists.—Beyond Yu-chi-kou, quartzites and schists lie against rhyolites and felsites. The metamorphosed rocks attain a thickness of hundreds of feet. The quartzites are dense and massive; the schists, closer to the rhyolites, are almost slaty, perhaps sheared by intrusion. T'an and Li examined the extension of these rocks to the northeast and found early Triassic plants, *Cladophlebis denticulata* Brongniart

[8] Y. T. Chao and T. K. Huang: *op. cit.*, p. 107.

and *Podozamites lanceolatus* (Lindley and Hutton), at Ching-kang-lin in Peng-hsien. These, together with the finds in the Min River section, indicate the same age for the section as for the Hsiang-chi coal series of Chao and Huang.

IGNEOUS ROCKS

General statement.—For 12 miles beyond the schists is a succession of igneous rocks of considerable variety and diversity of age. Thin sections show consistent post-intrusion hydrothermal action.

Andesites and rhyolites make up the first 2½ miles of the long igneous series, extending beyond Niang-tsu-ling Pass, at an altitude of 5,100 feet barometric, or almost 3,000 feet above Kuan-hsien. The river descends 1,000 feet in 14 to 15 miles. Beyond the rhyolites, for 10 miles, is a great abundance and variety of syenites and diorites.

Rhyolites are more abundant than andesites. These rhyolites, like the apparently much younger, more crystalline rocks next to them, were intruded between the diorites and the clastics. According to Chao and Huang, they were later intruded by a rock, which is now an altered green felsite, and, when squeezed into place, perhaps cooled into andesite and was then changed hydrothermally into propylite.[9] Chao and Huang refer to this igneous section as "predominantly greenstone while intrusive granite was also frequently met with."[10] They believed that the greenstone is older than the granites. Most of the coarse crystalline rocks are diorite and syenite; the greenstones are rhyolites and altered andesites or propylites. Thin sections, each collected at the place indicated by the number on the section, were studied.

Felsite No. 18.—An altered felsite, perhaps a propylite. Hand specimen—dense, dark-green, even, fine-grained, aphanitic; shows many small, continuous, white or greenish, vein-like streaks, which appear to be cemented joints; weathers rusty. Thin section—primary minerals: quartz containing apatite; feldspar, probably plagioclase, but now so altered that it cannot be determined. Secondary minerals: quartz, chlorite, sericite, all in large quantities; epidote and iron oxides, probably both magnetite and hematite, in small quantities. Originally, the chief mineral was probably feldspar, judging from the lath-like outlines, which the secondary mineral groups now assume. Most of the quartz is secondary after the feldspar. Texture and mineral content named above would indicate felsite; the original mineral content indicated by the secondary minerals suggests, perhaps, an andesite.

This "felsite" seems to have been intruded into the andesite (No. 17) and the rhyolite (No. 16) in bodies hundreds of feet wide, and to have cooled quickly and uniformly. Such a conclusion may seem anomalous, but the character of the rock and the size of the intrusion make other interpretations difficult.

Andesite porphyry No. 17.—Hand specimen—dense, black to dark-gray, containing many small phenocrysts of quartz and feldspar, which make up 10 to 20 per cent of

[9] Arthur Holmes: *Nomenclature of petrology* (1920) p. 189. Thos. Murby and Sons.
[10] Y. T. Chao and T. K. Huang: *op. cit.*, p. 107.

the rock. Thin section—primary minerals: quartz feldspars (sanidine, microcline, plagioclase), and hematite. Phenocrysts of quartz and sanidine, for the most part, show crystal outline. Microcline and plagioclase are rare. Phenocrysts of orthoclase range up to 2 millimeters in length and quartz up to 1.8 millimeters. In patches, the groundmass shows myrmekite structure and areas of perthite. Feldspars show no evidence of hydrothermal action. The groundmass is silicic, too fine to be determined. Scattered through the section are minute particles, probably hematite, which may be the source of the dark color in the hand specimen. This rock was intruded into the sedimentary rocks, and makes a sharp contact with those to the southeast; but, on the north, it grades into more acidic rocks of a coarser texture. No. 17 and No. 16, more resistant than adjacent rocks, form the pass and the ridge between the Min and the Yu-chi rivers. Here, the valleys are youthful, and slopes are steep and rugged, with little talus and mantle.

Rhyolite No. 16.—Hand specimen—aphanitic, dense, red rock, set with tiny quartz crystals and a few bars of feldspar up to 1 or 2 millimeters in length. Phenocrysts make up no more than 2 to 3 per cent of the rock. Thin section—quartz and plagioclase, at least in part primary (Pl. 1, fig. 1). Other minerals are calcite and hematite, but most of the rock is indeterminate. Quartz is most abundant, appearing in clusters and in little stringers of clear, rather even crystals, in two cases projecting from the wall, in a comb structure. The mode of occurrence of quartz indicates it is a later mineral, formed in some places as a fissure filling, in others as replacement. Secondary calcite, associated with the quartz, shows twinning. Scattered through the section are small grains of hematite and, possibly, ilmenite. An opaque mineral, white in reflected light, is probably leucoxene. The rare feldspar crystals were optically determined as near albite. The groundmass is indeterminable but is highly silicic. Evidence of hydrothermal action is present but not so strong as in No. 18.

Altered quartz diorite No. 13.—Taken half a mile to a mile beyond the Niang-tsuling Pass, it represents the igneous rock after the transition from rhyolite and felsite to granitoid rock. Most of these plutonic rocks are grayish, but greenish facies result if the ferromagnesian minerals predominate. Hand specimen—fine, even-grained, wholly crystalline, gray rock, consisting of about equal parts of dark-green and of white material. All specimens contain quartz, and all the rocks examined are hydrothermally altered. Thin section— primary minerals: feldspar, 50± per cent; hornblende, 40± per cent; quartz, 10± per cent, and titanite in wedge-like crystals; zoisite, sericite, and quartz, secondary after the feldspar. Saussuritization of the lath-shaped feldspar seems to be complete, and the abundance of zoisite points to calcium plagioclase as the primary feldspar. Hornblende is in euhedral crystals of about the same age as the feldspar but it is only partly altered to chlorite (Pl. 1, fig. 2). Much of No. 13 is unaltered. Primary quartz is in clear, relatively large grains, much of it enclosing hornblende and even feldspar, and, hence, later than either.

Altered quartz diorite porphyry No. 14.—Hand specimen—dark-green, fine-grained, with many white phenocrysts of uneven size, partly quartz, apparently, in many cases, not single crystals nor all of the same mineral; phenocrysts are more resistant to weathering than is the groundmass. Thin section—magnetite, augite, primary in the groundmass; phenocrysts probably andesine, as suggested by the relic lath shapes, although these are now completely saussuritized. Groundmass minerals are quartz, zoisite, chlorite, and badly corroded augite. In most cases, augite is fresh, although broken, and in places is altered to chrysotile. Magnetite is in both phenocrysts and groundmass. High birefringence of an iron-stained mineral suggests it is a carbonate.

Altered quartz diorite No. 12.—The sample was taken near the village of Yin-hsiu-wan, about 3 miles beyond the pass. In the field, the rock resembled diorite gneiss but the hand specimen shows no evidence of gneissic structure. Hand specimen—medium-grained, gray, dioritic rock, with noticeable feldspar and hornblende crystals in a finer-grained groundmass. Thin section—feldspar (oligoclase and andesine), with hornblende, augite, sphene, quartz, biotite, sericite, and magnetite. Feldspar is largely altered to sericite, some of it suggesting zonal arrangement; other parts are changed to zoisite and quartz. Original cleavage lines of the feldspar give the sericite a directional appearance. Where it is least altered, the optical properties of the feldspar strongly suggest andesine. Hornblende is nearly fresh, although it is corroded and shows absorption effects; some of it has changed to chlorite (Pl. 1, fig. 3). It crystallized after the feldspar. Accessory minerals are biotite, changed to chlorite and magnetite, wedge-shaped crystals of sphene, and rare grains of what appears to be olivine—some fresh, others partly altered to serpentine and magnetite. A little clear quartz, by position evidently later than feldspar and hornblende, fills the spaces. The whole mass is altered, mainly by hydrothermal processes.

A mile beyond Yin-hsiu-wan the diorite gradually assumes a darker color; it continues for about 7 miles, or almost to Hsin-wên-ping. Here and there, granitic and dioritic facies alternate, but all are much altered hydrothermally.

Near Chong-chien-lao, in the diorite section, where the stream swings close to the east bank, there have been landslides, one mass so large that it gives the impression of a rock hill in the valley. Its joints are discordant with the joint system in the diorite mass, and the great scar high up on the valley wall is further evidence of its landslide origin. Gravel terraces, probably due to ponding of waters behind obstructions, lie above narrow short sections of gorge or above big landslides.

From near Yin-hsiu-wan to the end of the igneous rocks, the whole mass is interwoven with scores of black dikes, ranging in thickness from several feet to only 2, 3, or 4 inches. The diorite is cut by granitoid dikes, one nearly white, with large feldspar crystals surrounded by quartz. Many of the dark dikes are basaltic, in places amygdaloidal, and they are the youngest dikes seen. One was sampled and is decribed as No. 9.

Altered porphyritic diorite No. 9.—Taken at Yin-hsiu-wan. Hand specimen—fine-grained, dark-green, even-textured, with large, tabular, white phenocrysts, up to 3 to 4 centimeters long, 2.5 centimeters wide, and 0.5 centimeter thick. Thin section—scattered phenocrysts, originally feldspar, completely saussuritized, consist of a mixture of 65 per cent zoisite, 20 per cent quartz, 10 per cent sericite, and a little chlorite, with possibly secondary feldspar. The phaneritic groundmass consists of intimately mixed chlorite, sericite, quartz, zoisite, magnetite, laths of feldspar, andesine (?), and hornblende (?). The original groundmass consisted of tiny feldspar laths, biotite, now altered to chlorite, and hornblende crystals, now in small relics. Outlines of the biotite are preserved in the mixture of zoisite, sericite, and quartz, and some unaltered crystals are andesine or oligoclase. Remnants of the hornblende are now chiefly chlorite, serpentine, and magnetite. This chlorite-magnetite association indicates that the rock may originally have contained rare olivine crystals. This dike is as much altered hydrothermally as is the country rock.

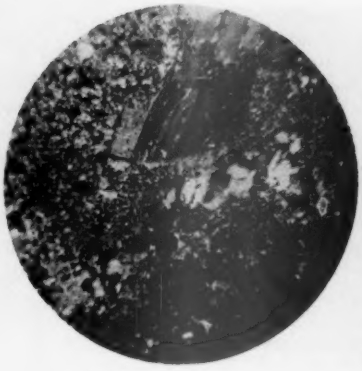

FIGURE 1. RHYOLITE, NO. 16
Large feldspar phenocryst, partly corroded (above center) in a fine-grained groundmass. Black patch (below center) is probably ilmenite as it has the white opaque leucoxene, a product of ilmenite weathering. Most of light material is a fragmentary quartz vein. x25.

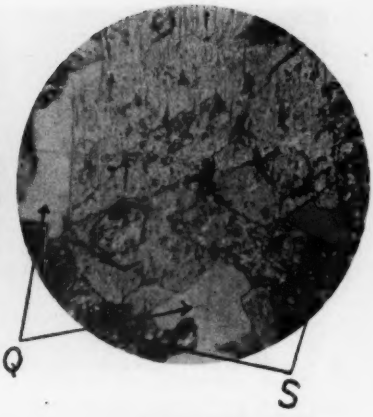

FIGURE 2. ALTERED QUARTZ DIORITE
Large crystal of hornblende, slightly altered, occupies most of the picture. Clear quartz (Q) with saussurite (S) derived from feldspar. x25.

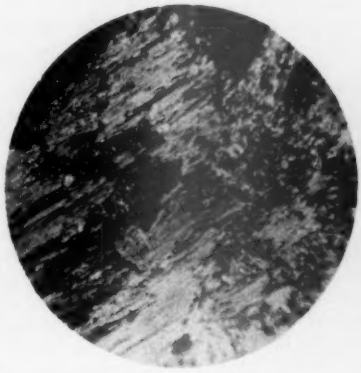

FIGURE 3. HYDROTHERMALLY ALTERED QUARTZ DIORITE
Field is occupied mostly by hornblende, partly changed to chlorite. At the edge, especially top and right, is feldspar, now saussuritized. x25.

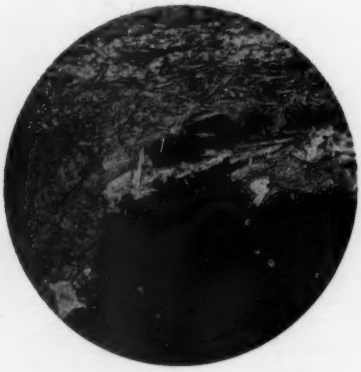

FIGURE 4. MUSCOVITE-QUARTZ SCHIST
Biotite (black) and chlorite (at edge of black) with sericite in small laths. x70.

PHOTOMICROGRAPHS

FIGURE 1. GORGE IN ALTERED PORPHYRITIC DIORITE NO. 9
Looking north, toward Hsin-wên-ping. Road here is cut in the valley wall, far above the water.

FIGURE 2. SILICEOUS CHLORITE SCHIST BELOW WÊN-CHUAN-HSIEN
Looking north upstream. Road with boulder stone wall (foreground), boulder fan (across middle), and two remnants of high-level fans as terraces (above). An old village is on the terraces.

FIGURE 3. THE GRANITE JUST ABOVE WÊN-CHUAN-HSIEN
Looking north, upstream.

SCHISTS AND QUARTZITES

A few hundred feet south of Hsin-wên-ping, the diorite gives way abruptly to schists. The valley widens and talus mantles the bedrock for about 2 miles. In the diorite zone, lofty, rugged snow-capped peaks rise on the west side of the stream (Pl. 2, fig. 1). For a mile along the road, chlorite-quartz schist talus conceals the rock; next, a competent quartzite, at least 1,000 feet thick, dips more than 80° NW and strikes generally from N 50° to 60° E. The rocks are twisted. Slabs show distinct bedding planes. Associated schists still carry bedding planes, cross-bedding, lensing of layers, grains (restored) of sand—evidences of a sedimentary origin—although now completely metamorphosed.

GNEISS AND DIORITE

Gneiss and diorite occupy the next 2 miles of the traverse. Here, the rock much resembles the diorite below the metamorphics just described, and the arrangement suggests that the schist-quartzite series is an inclusion, an interpretation supported by its shattered condition and skewed strike. The exact contact above the diorite is covered with talus.

INTRUDED METAMORPHICS

General statement.—Metamorphics, intruded with quartz veins, extend from just below Yin-hun-ping to the Pan-chiao limestones. The first member is green mica schist, which splits easily and is used for construction and paving.

Serpentinized marble No. 11.—Above the schists, for a few hundred feet, is a delicate green rock, known locally as "jade," meaning simply "ornament rock," but the stone bears little resemblance, except in color—and even that is too light—to the fine grades of jade worked and sold in south China. Hand specimen—fine-grained, crystalline, even-textured rock, delicate greenish-white, varying slightly from place to place, abundantly effervescent, and easily worked. Long, slender, white or clear needle crystals penetrate the mass in every direction. Thin section—calcite, 90 per cent in well-formed, interlocking crystals; interwoven with small fibers of chrysotile, 8 per cent; possibly traces of quartz. The color is probably due to the chrysotile. The outcrop extends obliquely up the valley wall. Lack of dolomite in the marble suggests introduction of magnesium silicate. No micas were seen.

Fissile chlorite schists and thinner quartzite beds occupy a mile of the traverse. They represent metamorphosed sediments and are shot with light and dark dikes.

Diorite porphyry.—Selected from an outcrop 2,000 feet wide, below Sha-li-kuan. Hand specimen—white, lath-shaped feldspar phenocrysts, varying in size up to 3 or 4 centimeters by 2.5 centimeters by 0.6 centimeter. Some are tabular, others more or less square in cross section. In places, they diverge, making rosettes, a striking feature in the valley wall. Some crystals interpenetrate, as if they were synchronous; others have grown around each other, as if some were later. Many of the crystals seem to have been broken, faulted, doubled up, or pulled apart, as if, subsequent to their growth, stiff magma had flowed and broken them. A few phenocrysts show a streak of the dense groundmass between two parts of the crystal. In

parts of the black groundmass there are many small black crystals. In other parts the texture is wholly aphanitic. Thin section—large phenocrysts are feldspar laths, probably oligoclase and andesine saussuritized to zoisite, sericite, and calcite; magnetite, hornblende (?), and biotite; small phenocrysts, some only partly altered; and probably hornblende wholly or partly altered to biotite, chlorite, and sericite. The remainder, or about 75 per cent of the whole rock, consists of extremely small opaque or dark grains, some of which are transparent, resembling chlorite and sericite; others are magnetite. The alterations are the result of hydrothermal action. This rock has three distinct generations of crystals.

Chlorite schist.—Chlorite schists, about 1,000 feet thick, and similar to the schists south of the diorite porphyry, stand nearly vertical. They were separated from similar rocks to the south by the intruded diorite porphyry.

Granite or diorite gneiss.—Near Sha-li-kuan, sometimes called Chaping-kuan, the formation next to the schists is gneiss, 3,000 to 4,000 feet thick. Its minerals are feldspar, in part plagioclase, quartz, and hornblende. The gneiss was intruded before the folding and regional metamorphism, for it is a metamorphosed igneous rock.

Chlorite and quartz schists.—Next, a mass of schists, in part siliceous and quartzitic, in part greenish chloritic, dips steeply north at angles of 75 to 80 degrees and strikes almost east. The boundary between these schists and the gneiss to the south is not sharp but is obscured by much contact, and some regional, metamorphism. The presence of the common criteria in these schists suggests their sedimentary origin.

Tao-kuan granite and granite gneiss.—The granitic rock, next, was not sampled. Banding shows the effects of regional metamorphism. Dikes, apparently of diorite, penetrate the rock, and three-quarters of a mile south of Tao-kuan, a dike of diorite porphyry, 45 feet thick, with laths of feldspar .3 centimeter by .6 centimeter by 3 to 5 centimeters, cuts through a dense, fine-grained, dark variety of the diorite. The dike probably is from the same magma as the main granitic-dioritic body, but it is a portion that was squeezed up into earlier intrusions. The contact of the main body with the next rock upstream is less definite than is its southern contact. Valley walls in these resistant rocks are steep, in places at angles more than 45 degrees.

So-chiao complex.—For nearly 4 miles, two on each side of So-chiao, is a confused, complex series of gneiss, schist, granite, and diorite, interpenetrated by dikes and masses of dark to black peridotite and gabbro. The dominant rock is a granite gneiss. A mile below So-chiao and at the town, it contains two intrusions of diorite, several hundred feet across. A mile above the village, a wedge of green chlorite-quartz schist intrudes the gneiss much like that just above Sha-li-kuan. This wedge is prob-

ably 1,500 feet across at the road level and narrows downward. Beyond this schist, the gneiss is intruded by more granite, like that at So-chiao. Dark dikes are more numerous at the northern end of the complex. They maintain sharp contacts with the older rocks; they have not produced much metamorphism but usually have chilled borders, with coarser-grained interiors.

Chlorite-quartz schist.—A mile or two below Wa-yao-ping, another thick body of green chlorite-quartz schist dips 75° to 80° NW and strikes N 70° E. It is 4,000 to 5,000 feet wide and contains several dikes of granite of different ages. The earlier ones show metamorphism to gneiss but many are only hydrothermally altered.

Massive quartzite.—Below Wa-yao-ping, a strong, massive quartzite, fully 1,000 feet thick, makes a rib down the valley wall. Its dip is about 70° NW; the general strike is close to northeast.

Siliceous chlorite schists.—From Wa-yao-ping to Pei-yü-lo, a distance of 3 to 4 miles, rocks of sedimentary origin, resembling the chlorite-quartz schist already mentioned, dip northwest with a strike of N 60° E (Pl. 2, fig. 2). Intruded into them north of Wên-chuan-hsien are two large granitic bodies (Pl. 2, fig. 3). The first is 2,500 to 3,000 feet thick and carries a great inclusion of schist and dioritic gneiss. The second is probably older, for it is gneissic. Aside from the gneissic structure, the two bodies look much alike. A sample of the more southern intrusion is described as No. 8.

Altered granite No. 8.—Hand specimen—light-gray, even-grained granite, stippled with tiny black and large pale-green patches. Large quartz and feldspar grains. Thin section—feldspars (albite, oligoclase, orthoclase), 35± per cent; quartz, 35± per cent; biotite, 10 to 15 per cent; green hornblende, 5 per cent; magnetite, 2 to 3 per cent. Small apatite crystals are enclosed within feldspar, which is saussuritized to zoisite and sericite, and rarely to epidote. Hornblende is altered to chlorite and magnetite. Biotite, the main femic mineral, is partly altered to chlorite. Optically, some quartz shows strain. Hydrothermal action[11] is indicated by saussuritization and by deuteric intergrowths of quartz and albite, which form myrmekite.[12]

Green chlorite schist.—For more than a mile above Pei-yü-lo, there are green schists much like those seen repeatedly throughout the 18 to 20 miles just traversed. They show evidence of sedimentary origin, but are much intruded with coarse crystalline rocks, which in some places resemble granite, in others, gneiss. Probably, the gneissic bodies are older and have been included in the regional metamorphism; the others are younger, showing only hydrothermal effects. An irregular body of granite, several

[11] J. J. Sederholm: *On synantectic minerals and related phenomena*, Comm. géol. Finlande, Bull. 48 (1916).

[12] F. F. Grout: *Petrography and petrology* (1932) p. 243.

hundred feet wide, is squeezed between these metamorphosed sediments and the next member, a chlorite schist. No samples of the granite were taken, but the schist is described as No. 7.

Chlorite-feldspar schist No. 7—Hand specimen—fine-grained, greenish-gray, chlorite schist, carrying some larger white crystals of feldspar, part of which is weathered with iron stains. Thin section—primary minerals: feldspar (albite, oligoclase, orthoclase), about 50 per cent; quartz, and green biotite; secondary minerals: chlorite, quartz, calcite, pyrite, biotite, sericite after hornblende, remnants of which still persist. Some quartz is in large grains and shows strain; some is in small grains and seems to be recrystallized; primary feldspar is covered with sericite and shows strain. The slide shows little evidence of the schistosity seen in the field, even though the hand specimen is obviously a schist. Small grains of green biotite, quartz, chlorite, and sericite are strung out, giving a schistose appearance.

Minerals found in this rock set it off genetically from the long section of schists. The feldspars, hornblende, and the large quartz grains point to an igneous origin. A quartz monzonite is suggested both by the types and by the texture of the feldspars.

PAN-CHIAO LIMESTONE

A series of beds of limestone, some thick, others thin and shaly, or even quartzitic, crops out along the road for a mile and a half, three-quarters of a mile each side of Pan-chiao. Dips are 75° NW; the strike is N 45° E. The rock is cherty, with hackly fracture; fossils are rare. When studied in the field, these limestones were believed to be the same beds as those below Yu-chi-kou, although they are thicker here and are associated with more shales or schists and less sandstones and quartzites.

MO-DAO-CHI SCHISTS AND GNEISSES

General description.—Beyond the limestones, for more than 2 miles, is a thick series of metamorphic rocks. Between the limestones and the metamorphics, the boundary is distinct, like a bedding plane, and many of the schist horizons show abundant evidence of sedimentary origin. The stream flows for 2 or 3 miles along the strike, possibly exposing a repetition of the schist above Pei-yü-lo. In the central part of the schists is an inclusion of diorite, 300 to 400 feet in width; its boundaries are fairly definite, but they are not straight. A specimen is described as No. 6.

Altered diorite dike No. 6.—Hand specimen—even-textured, medium-grained, dark, greenish rock, spattered with whitish, indefinite feldspar crystals. Minute pyrite crystals are present. Thin section—primary minerals: quartz, feldspar (oligoclase, andesine), and green and brown biotite. Remnants of what seems to be primary augite are found in some masses of chlorite and uralite. Feldspar crystals, up to 2 millimeters in length, are surrounded by secondary chlorite, quartz, and calcite; the probable augite crystals are surrounded by epidote, uralite, biotite, chlorite, and calcite. Primary biotite is altered near the edges to chlorite. Feldspars are filled with minute inclusions of hydrothermal sericite. Comb structure and extinction directions of some of the quartz, which makes up about 8 per cent of the slice, suggest

mineralization after the rock had cooled; the pyrite, titanite, ilmenite, and leucoxene offer additional evidence. This dike was probably involved in the regional metamorphism, as well as in the pneumatolitic action.

CHI-PAN-KOU QUARTZITE SCHIST

The town of Chi-pan-kou stands on a mass of quartzitic schist, about 4,000 feet wide, details of which are concealed by water-worn and angular waste. It seems to be quite variable, with thick and thin lenses. Its clastic origin has not been doubted. The dip is consistent with the beds above and below. The apparent outcrop of this schist between Wei-chou and Yen-men-kuan is made quite possible by the strike of N 45° to 55° E.

WEI-CHOU LIMESTONES AND MARBLES

General description.—In the next 4 miles along the road, the rocks are dominantly calcareous. Strikes are uniformly N 40° to 65° E, and dips vary from 44° to 65° NW with notable local departures (Fig. 2). In their summary, Chao and Huang [18] give no thicknesses for individual units, but it seems possible to correlate most of their units with these. No fossils were collected; the rocks are exceptionally barren. Fossils collected by T'an and Li indicate that some of the limestones are of Devonian age. The Director of the National Survey furnishes the following information: "Outside of the east gate of Wei-chou city T'an and Li collected fossil corals of Devonian species and farther east of Permian species." From these identifications made by Mr. Chi, of the National Geological Survey, the writer assumes an overturned fold in the rocks; thus, Permian strata are southeast of Devonian, the entire sequence dipping northwest. The same geologists consistently report Devonian corals at Mao-hsien, a few miles up the river.

Such thick limestones are comparable with the early Paleozoic beds in the Yangtse gorges and in the Appalachians. For convenience, three divisions have been made, two of which are pure limestone, and one a gray mica schist.

The southern portion consists of several hundred feet of limestone beds, highly silicified, very cherty in two horizons, one of them central, the other (on the north side) probably stratigraphically lower. Some of the beds are excellent gray, blue, and yellow marble; others have been little altered and are simply massive, dense, blue limestones, or crystalline white beds. Dark-blue and white layers alternate at intervals of an inch or two. Impurities are crystallized by metamorphism into mica and other accessory minerals; notable sandstone and shales form partings. A sample is described as No. 4.

[18] Y. T. Chao and T. K. Huang: *Geology of the Tsinlingshan and Szechwan*, Geol. Surv. China., Mem., ser. A, no. 9 (1931) p. 108.

Light- and dark-banded crystalline limestone No. 4.—Hand specimen—irregular, white and dark-gray to blue, banded limestone, unevenly crystalline. Dark color may be caused by carbon, although no graphite crystals were found. Completely soluble, giving darkened liquid; no trace of magnesium or iron; a bare trace of silica, and an abundance of calcium carbonate. Thin section—calcite, 97 per cent; quartz, 0.5 per cent; argillaceous material, 2.5 per cent. Irregularly sized grains of calcite, 3 millimeters to submicroscopic, average .15 millimeters; grains of the same size in bands, or, more rarely, in clusters; quartz in some places clear but most of it filled with inclusions.

This member is probably Permian. It dips northwestward beneath the next member, but it contains Permian fossils; the next member bears Devonian forms and dips the same way. They are considered to be two members of the south limb of an anticlinal fold, overturned to the south and nearly closed (Fig. 2). Two fault zones are placed in the section, though not seen, because no other possible interpretation would fit the facts.

The next member consists of several hundred feet of crumbly, somewhat cherty and silicified limestone with hackly fracture; is apparently repeated beyond the gray mica schist member. It was examined in the road up the west branch above Wei-chou and on the east branch, because the Min River flows almost along its strike for some distance above Wei-chou. Here, it is marble, varying much in size of grain. Many feet of micaceous schist separate great series of marble layers, which grade into the mica schists folded between the two outcrops of the limestone. Two samples taken are here described. The first, No. 2, came from the northwest limb of the fold; the second, No. 3, came from the south limb up the Min toward Yen-men-kuan.

White marble near Wei-chou No. 2.—Hand specimen—white, crystalline, medium, even-grained, small flakes of pale greenish talc, yellow streaks along occasional planes; strong reaction for calcium, but only traces of magnesium, silica, and iron. Thin section—calcite, 98 per cent; quartz, 2 per cent; talc, in traces and only along well-defined surfaces. Calcite, in even-sized interlocking grains, all well crystallized, twinned, ranging from .10 to .15 millimeter; quartz in small grains 1 millimeter or less, clear, rounded to subangular, with small, rounded inclusions, which may be sand grains. The yellow streaks seem to be iron stains coating calcite crystals along cracks.

Yellow marble at Yen-men-kuan No. 3.—Hand specimen—taken three miles northeast of Wei-chou; fine-grained, dense, yellowish-white marble with a talc-like foliated mineral in irregular layers; soluble in hydrochloric acid, leaving a faint white residue; calcium, abundant; magnesium, scarce; traces of iron and silica. Thin section—calcite, 95 per cent, in a jumbled mosaic of small crystals mingled with scattered minute flakes of kaolin, 2 per cent, and flaky talc, yellowish to white or even greenish. Quartz grains, 3 per cent, with tiny crystal outlines arranged in rough banding; grains filled with unoriented inclusions. The jumbled mosaic is consistent with the coarser field confusion. The rock has been fractured and recemented by deposition of calcite. Beds usually too thin for use, bent, contorted, greatly folded and crumpled, yet wholly crystalline.

These beds are the ones in which T'an and Li found the Devonian fossils, and, no doubt, they are the oldest limestones seen.

The third member, a gray mica schist, pinched in between the folds of the limestone, extends almost up to Wei-chou and probably has a thickness of 400 or 500 feet. It is of sedimentary origin and has consistent dip and strike. Possibly 50 per cent of the material is repeated because it is folded in between the limbs of limestone. It was examined at many places of intersection with the road or with the Min River, south of Wei-chou, and along its strike up the east branch. Calcareous layers in it are completely changed to marble.

MUSCOVITE-QUARTZ SCHIST

"Mica knot" schist No. 1, upstream from the calcareous series, can be studied on the west branch for a mile above Wei-chou; the thickness is from 4,000 to 5,000 feet. The dip is 45° to 65° NW, the strike, N 40° to 45° E; bedding is thin, up to an inch or more; schistosity is strong, causing almost a slaty cleavage in many places.

Hand specimen—lustrous, silvery-gray to greenish muscovite thoroughly interspersed with quartz. Definite siliceous layers thicken and thin along the strike. Large flakes or bunches of biotite are arranged more or less in rows or planes. The rock is not strong, and it contributes much waste to the stream. Thin section—muscovite and quartz make up a large proportion of the rock. Biotite, chlorite, magnetite, clinozoisite; muscovite in small laths, about .01 to .04 millimeter wide and .1 to .5 millimeter long; biotite, brown in porphyroblastic clusters, up to 2 millimeters wide, in some places altering to green chlorite and magnetite (Pl. 1, fig. 4). Biotite and quartz, not oriented with schistosity but in distinct layers associated with quartz grains and lenses. In some instances, chlorite is secondary after garnet and shows abnormal interference colors, especially blue. The inner parts of these clusters still show the isotropic garnet, and, rarely, the outlines of garnets in bodies 1 to 2 millimeters across. Biotite and garnet porphyroblasts evidently were developed after the regional metamorphism.

The hand specimen shows cross-bedding and lensing of layers; in the field the bedding is continuous with that of the calcareous rocks; rounded grains are seen under the microscope. Thus, three lines of evidence point to a sedimentary origin.

Typical beds attain a total thickness of 500 feet or more, becoming more siliceous to the west and more micaceous to the east. Beds are mashed, contorted, and variously weathered. Some varieties weather with large, rounded holes several feet across, so that a bluff, rising hundreds of feet, is honey-combed in a large pattern (Fig. 3). Where weathered loose, the soft mica has an almost talcose feel, and may be sericite.

EPIDOTE-SERICITE SCHIST

Between the marbles and the muscovite-quartz schist is a great wedge of dense, green rock, varying to purple and blue in places. It weathers to a dirty white surface, which clearly reveals the schistosity and an

intertwining to threads of minerals of different kinds. This rock (No. 5) was finally termed a felsite, but at first glance it resembles a fine-grained quartzite. Its schistosity, although scarcely visible in the gross field

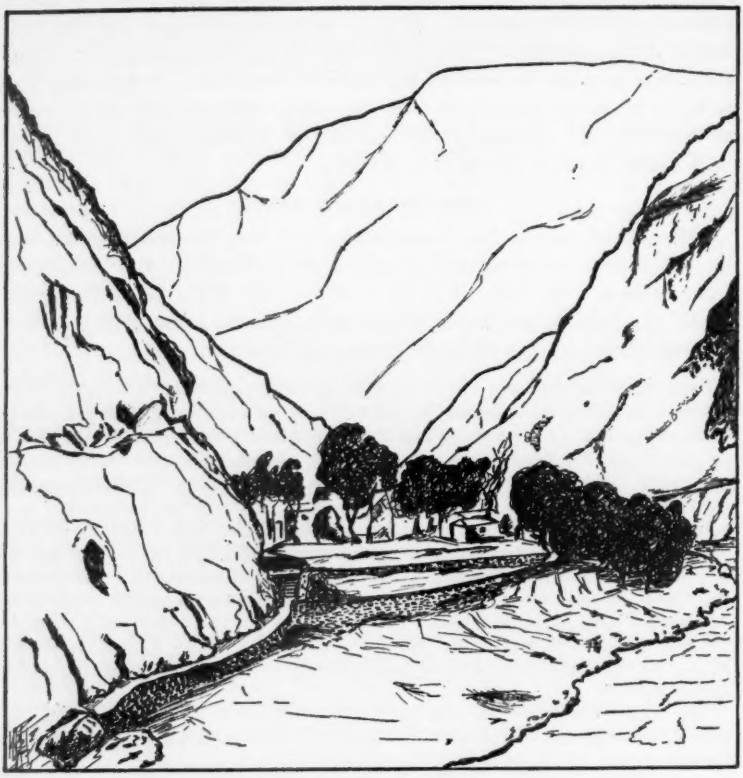

FIGURE 3.—*The Hsiao Ho*

Looking toward Li-fan, in the muscovite-quartz schist. Valley walls are ragged, not only because of honeycomb weathering but also because of splintering and falling of schist.

structures, is so accentuated by weathering as to be seen readily through a hand lens and it is seen clearly in thin sections.

Hand specimen—a fragment, bounded by joint planes that yield wedge-shaped pieces; joints parallel with the strike; none across the strike or schistosity. Thin section—quartz, sericite, epidote, ilmenite, leucoxene, and probably chlorite and zoisite. Fine texture makes identification difficult. Fine grains of quartz, often in bands around what seem to be minute flakes of both sericite and chlorite. Weathered grains of ilmenite are surrounded by its secondary product, leucoxene. Saussurite (?) and zoisite (?) point to former feldspathic phenocrysts. Quartz banding may suggest

a sedimentary origin, but the hydrothermal action, common throughout the section, is competent to produce all banding seen. Composition in general, together with the presence of epidote and ilmenite, strongly suggests an igneous origin for the rock. The great wedge shape of the mass is even better evidence. At Wei-chou, and westward, the last marble and the muscovite-quartz schist lie in contact and are both of sedimentary origin. East of Wei-chou a few hundred feet, the blade of this wedge of schist comes between them, and, in the next 3 miles, it thickens or widens to fully 2,000 feet. It seems to cut across some of the marble beds near Yen-men-kuan. The fine-grained patches may indicate saussuritized feldspar. Shape, position, and mineral composition support the interpretation that this mass is an igneous intrusion. It has been subjected to the regional metamorphism, which caused its schistosity, and later to hydrothermal alteration so common in the Min River section.

This wedge of intrusives may be related to the problem of the fold near Wei-chou, already described.

OTHER ROCKS NEAR WEI-CHOU

The Wei-chou "jade dike" is not true jade, although it is worked for ornamental stone. It is a body of limestone changed by regional metamorphism to marble, and partly silicified by heated waters, which had access along joints and cracks.

Above Wei-chou, on Hsiao or Tsa-ku-lao River toward Li-fan, is a rich graphite schist, which strikes in a direction that would carry it across to the Min at, or above, Mao-chou, or Mou-hsien, beyond the limit of the area studied.

The valley up from Wei-chou, toward Li-fan and the Tibetan interior, is narrow, youthful, and impressive (Fig. 3). In places, walls rise as steeply as 80 degrees for 1,000 feet or more, and many slopes are steeper than 60 degrees for a height of a mile. Thus, in places, the angle between bluffs of the V-shaped gorge is only 60 degrees.

INTERPRETATIONS

THICKNESSES AND FUNDAMENTAL STRUCTURE

Only estimates of thicknesses were made. The distance from Kuan-hsien to Wei-chou, in a straight line, is 40 miles; by road, 60 miles. Correcting the distance between the end towns, 40 miles, by using the mean strike of about N 54° E, the estimated distance across the structure approximately at right angles to the mean strike is 25 or 26 miles. As the dips range from 90 to 65 degrees and average considerably more than the smaller figure, the thickness of rocks represented in the section approximates 23 miles. The various kinds of rocks have been carefully indicated on the section (Fig. 2) with reference to villages, and their actual thicknesses calculated as percentages of the 23 miles of thickness, with the following results:

Sediments: 15.5 per cent; metamorphosed sediments: 44 per cent; igneous rocks: 25.3 per cent; metamorphosed igneous rocks: 15 per cent.

In the section, there are less than 14 miles of sediments and about 9 miles of igneous rocks—i.e., the sedimentary section has been extended 65 per cent of its original thickness or length by intrusion. Many of these intrusions are transgressive; some may be concordant. This estimate of the actual thickness of sediments must be further modified because there are folds and thrust faults in the section; some portions are repeated, others are eliminated. The actual amount of repetition could not be determined in the hurried examination made. Even though local folds and faults are recognized, the fundamental structure is probably a geanticline.

Five lines of evidence are presented in favor of the presence of the large anticlinal structure. (1) In general, the dips reverse in the section. Although all observed dips are steep, most of those in the southern part are southerly, and most of those in the northern part are northerly. (2) The strikes are similar, nearly parallel, although a little more nearly northeast in the northern part, as if the anticlinal structure pitched gently to the southwest. However, Chao and Huang do not report such a structure in the Fu-chiang Valley, 30 to 50 miles to the east. (3) The limestones on opposite sides differ in character much less than in thickness. They could not be expected to be identical over so great a distance. Most of the sandstones are associated with the limestones, whereas a great body of shales, with scarcely any sandstones or limestones, is exposed in the middle part of the fold. Permian foraminifera on the south side and other Permian species on the north side, above Devonian species, suggest a large anticlinal structure, even though both the Permian series are in an overturned sequence. The axis of the fold has been put provisionally in the central part of the shales, now schists, or near So-chiao, irrespective of the intruded bodies. (4) Metamorphism of the regional or flow type does not reach the margin of the fold; it becomes more intense toward the postulated axial region because of former greater cover or because, in the folding, the rocks were brought up from greater depths, and the crushing pressures were greater in the axial portion than on the flanks. (5) Intrusions are older and more abundant toward this axial region. This is particularly true if the rhyolitic intrusions in the vicinity of Niang-tsu-ling Pass are not included. Moreover, in this central region, the intrusions are not disposed as sills between the strata but as large bosses or rounded laccoliths in the schists. Their contacts are not flat planes but are rounded and irregular, partly obliterated surfaces.

Very little evidence that the structure is not an anticline could be found. The great size of the structure and the differences between the strata on opposite limbs may be arguments against the anticlinal interpretation. The approximate uniform dip might be suggestive of a monocline, but a monocline of 14 miles of strata nearly on end, without repetition, is a

long section. More probably, it is a repetition of strata in inverse order. All other facts seem of simpler interpretation, on the supposition that the rocks are in a geanticline, with at least one small fold near each end.

INTRUSIVE CONTACTS

Although there are intrusions of many kinds of rocks of many ages and intrusions into nearly every type of rock in the section, actual contact metamorphism is rare. Chilling of dikes is common, and a little rearrangement or reorganization of the substances of the minerals along contacts is recognizable, but mineralization is almost unknown. Ten to twenty miles east of the southern part of this section, cupriferous pyrite and chalcopyrite are worked, and Chao and Huang [14] report galena in this section in some intrusive series, but no workable deposits are known in the valley. This is remarkable when the great amount of regional metamorphism and of intrusion is noted. In keeping with the general absence of contact metamorphism, many of the contacts are sharp enough to be found and traced. This may well be interpreted to mean that the great bodies of gneiss are not fused or remade sediments. Such gneisses do not grade into other rocks, but lie within true metamorphics, schists in general. Contacts in the central part are not so sharp as those nearer the southern end of the section.

AGE OF THE ROCKS

Very little evidence has been found to suggest specific ages for the rocks, or dates for the events. The position, stage of metamorphism, and general associations, suggest a Paleozoic age for the great limestones, both in the southern and in the northern parts of the section. In adjacent valleys, Chao and Huang and the writer found corals and brachiopods in limestones that strike into those just above Kuan-hsien. These fossils are believed to be Silurian. The Devonian and the Permian fossils found by T'an and Li at, and east of, Wei-chou, and Permian forms north of the coals also help to fix the geologic age of the section. Probably, the central part of the section is older than are the ends. Chao and Huang [15] make a structure section in which they indicate a Cretaceous age for the coarse conglomerate at Kuan-hsien and a Jurassic age for the coal-bearing shales and sandstones, but later studies indicate the latter are early Cretaceous. This is in harmony with the hypothesis that the rocks are older northward in the section. At the north end, the order is reversed, the younger Permian beds lying north of the Devonian.

Inasmuch as the coals and coarse conglomerates involved are Cretaceous, the folding is comparatively recent, possibly post-Cretaceous.

[14] Y. T. Chao and T. K. Huang: *Geology of the Tsinlingshan and Szechuan*, Geol. Surv. China, Mem., ser. A, no. 9 (1931) p. 108.
[15] *Op. cit.*, p. 106.

REGIONAL METAMORPHISM

Subsequent to the deposition of the sediments, of which there are at least 7 or 8 miles in the series, with many horizons repeated, much regional metamorphism has occurred. But, as large portions of the igneous rocks, three-eighths at least, are gneisses among the schists and apparently changed with them, it is fair to place the time of their intrusion before the regional metamorphism. The coarse crystalline texture of the rocks suggests their deep-seated origin and calls for extensive erosion to remove their cover since their deformation. Their metamorphism is commensurate with that of the shale-schists associated with them.

The regional metamorphism finds expression in many changes: (a) cementation of sandstones and recrystallization into quartzites, with some development of mica in the flanks of the structure; (b) recrystallization of the limestones, particularly on the north limb, where not only is the texture that of marble, but also various impurities in the calcareous rocks are reorganized into talc, quartz grains, muscovite, and other species of mica; at the same time, any fossils that may have been in these rocks have been nearly obliterated; (c) shearing and strain in both individual mineral grains and in the rocks, caused by pressure and movement. In many places, minerals are oriented, and, in some of the chlorite schists, plications and close little wrinkles have been developed; (d) in the early igneous rocks, development of definite orientation of biotite and other dark minerals and of shear strains in feldspars and other minerals. A gneissic structure prevails throughout the mass, even though not all thin sections reveal it. In most instances, this metamorphism is to be credited to regional influences of pressure, shearing, and heat of compression, together with water activities. All sediments and intruded bodies have been modified consistently throughout the central two-thirds of the section.

SUBSEQUENT CHANGES

Many intruded bodies have been described, and hundreds more were seen that do not share in the regional metamorphism. Obviously, those that do show hydrothermal action were in place before such action occurred. This group includes all collected specimens of igneous origin except the andesite porphyry No. 17, which is far to the south, at the Niang-tsu-ling Pass. The altered felsite, propylite No. 18, believed by its field associations to be later than the rhyolite and the andesite porphyry Nos. 16 and 17, shows hydrothermal action; the andesite porphyry shows structures developed in the last stages of cooling, but no hydrothermal action. Its sanidine is still clear and has sharp boundaries. The lack of hydrothermal changes may be due to its distance from the central part of the structure. No. 16 has been hydrothermally changed.

Hundreds of small dikes ranging from rhyolites to basalt in composition cut through the section in many places and in many directions and are free from hydrothermal effects. Therefore, they are believed to be due to later intrusions.

The hydrothermal effects have reached igneous, as well as sedimentary, rocks. In igneous bodies, feldspars are universally altered to saussurite, sericite, zoisite, quartz, and a few other minerals; ferromagnesian minerals are altered to chlorite, magnetite, quartz, epidote, leucoxene. Garnets in schists have been almost completely destroyed, and chlorite and other secondary minerals are left in their places. Limestones are silicified and, in places, threaded with chrysotile, talc, and serpentine.

SUCCESSION OF EVENTS

A brief outline of the events that have transpired in the region is as follows: sediments were deposited first—shales, then sandstones and limestones, thin shales and sandstones associated with coals and carbonaceous shales and the Cretaceous conglomerates and breccias—then came intrusions. By this process, diorite and granite gneisses were thrust into the shales in eight to twelve places between Yin-hsiu-wan and Pei-yü-lo, in masses measuring from a little less than a mile up to 4 or 5 miles at the road level. Some of them thicken downward, notably those near Tao-kuan, So-chiao, and Wên-chuan-hsien. Some of them, doubtless, unite downward. These intrusions preceded uplift, folding, and the accompanying metamorphism. The sedimentary layers surrounding them, as well as the intrusions, were tilted on end and metamorphosed.

After this, and probably after much erosion, came other intrusions, such as the diorite porphyry No. 10, south of Sha-li-kuan, and the quartz diorite No. 13 near the high pass, which are too late to be affected by the regional metamorphism. After such intrusions came general hydrothermal activity, which modified the igneous rocks of both the early and the later intrusions. These hydrothermal effects are shown in many of the metamorphosed sediments as well as in the rocks of igneous origin, but they do not extend to the southern limits of the section. The red rhyolite No. 16 shows the action of heated waters, but the andesite porphyry No. 17 is almost unaffected. The latter lies against the quartzites and schists of the coal series, which it has modified, and must, therefore, be later than early Cretaceous. The writer believes that the heated water vapors came up along the axial portion of the main fold and diffused outward and upward along the strike of the structure.

After the hydrothermal episode, probably more uplift, though no more folding, occurred, and erosion continued. Likewise, subsequent to this hydrothermal altering of the rocks, scores of minor intrusions or dikes, ranging from a few inches to a few feet in thickness, have been squeezed

into joints in both igneous and metamorphic rocks. These are nowhere touched by the hydrothermal influences, which fact in part establishes their date.

RECENT PHYSIOGRAPHIC HISTORY

Not long ago, considerable uplift rejuvenated the streams. This uplift may be correlated with the disturbance that gave the Yangtse River opportunity to cut the gorges above Ichang, just as the great fold may be

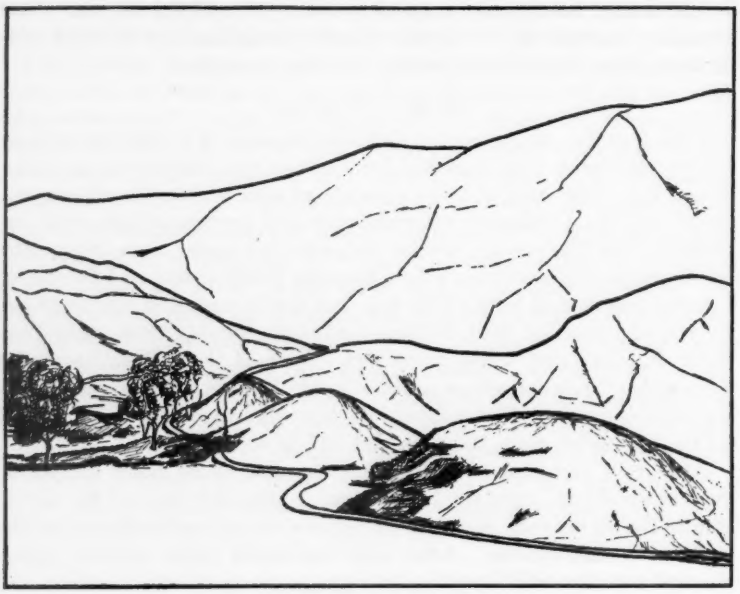

FIGURE 4.—*Sand dunes at Shao-tsi*

Shao-tsi means sand-holetown. Valley is broad in soluble limestones, partly marble, and weak shaly schists.

correlated with the series of folds that extend from northeast to southwest, obliquely across eastern Szechuan.

This uplift has permitted the cutting of the Min gorge, hundreds to thousands of feet deep, and the carrying out of waste to build the great Chengtu plain, a fan 2,000 square miles in area. This deep cutting exposes the section here described, constructs many fans of coarse rock at the mouths of tributaries of the Min, and causes great landslides from the steep valley walls into the gorge. Many slides occur up the tributaries also.

One of these landslides is probably responsible for the abundance of sand in dunes and terraces along the valley a mile or two above Shao-tsi (Fig. 4). According to tradition, detritus blocked the Min Valley at about the beginning of the Christian era, and "no water flowed down the valley for three days." Two places were seen below the sands, where remnants of great waste heaps still persist. Probably these are not parts of the landslide that stopped the waters nearly 2,000 years ago, but they may be remnants of one that ponded back the waters in which the sands of the dunes were laid. As the obstruction was finally cut away, the sands, left on any valley parts that could support them, were blown into the present dunes, so carefully described by Chao and Huang.[16] According to local reports, landslides up laterals were holding two lakes at the time of the writer's visit. Such lakes, should they burst their barrier dams suddenly, would sweep quantities of waste into the main valley. An earthquake, on August 25, 1933, caused a great landslide above Wei-chou, which held waters back for some days. When the dam broke, it caused a serious flood down the valley to Kuan-hsien. Heavy local rains do the same thing; such a local torrent does not greatly augment the Min but only shoots much more waste into the main valley than the river can remove. Débris has been known to pile up, 100 to 150 feet high, across the Min and to pond back much water. Such a case occurred about 1.5 miles above Wên-chuan-hsien. The stream has now cut through the waste, but it still has a strong boulder rapids there. Where waters are temporarily ponded, lateral fans and landslides in the ponds are more or less leveled to the water surface. Then, when the water escapes and cuts out part of the obstruction, these level-topped piles are left as terraces. This process accounts for some of the loose rock terraces in the valley. Some such terraces have witness to their landslide origin in great scars high on the bluffs above.

ECONOMIC PRODUCTS

CALCAREOUS ROCKS

The limestones are generally almost pure calcium carbonate and, where free from shaly or schist streaks, burn to excellent lime. The more massive beds are used just below Yu-chi-kou, where several kilns along the stream are operated. Coal is used for fuel to burn the stone, and an active lime is produced. The lime cannot be carried by water to markets downstream because of the danger of wetting and slaking on the native rafts. Therefore, it goes as far as Chengtu in baskets on poles swung over men's shoulders.

[16] *Op. cit.*, p. 111.

Marble, locally called jade, is worked at the twin villages of Yin-hun-ping, more than 20 miles up the stream above Kuan-hsien. The stone is quarried hundreds of feet up the valley wall in lateral ravines and is brought down to shelters beside the road, to be fashioned. Several ornaments are made of it, but the wrist ring is probably the most common. Because the rock is mostly calcite, it cuts easily. A cylindrical drill, nearly 2 inches in diameter, is used to take out a core through a slab of rock. Then a similar drill, about 3 inches in diameter, is centered on the hole and is drilled through the slab again, thus producing a stone tube. Next, this tube is sawed transversely into rings about half an inch in thickness. Careful workmen then proceed, with cutting stones, sand, and powders, to make the square cross section of the ring round and smooth. Thus, the product is about ready for market when it leaves the Yin-hun-ping lapidary. Near Wei-chou, a similar so-called "jade dike" is worked. So far as could be learned, no use, except for a few ornaments, is made of the marble as such near Wei-chou. It is used for rough work only—walls, walks, and crude stone buildings.

OTHER SEDIMENTARY ROCKS

Sandstones are abundant in every stage of cementation, from those too friable to resist the weather to those so firmly silica-cemented as to be difficult to work. The only place at which sandstone has been opened for quarrying is near Ba-sha, where ancient pits are still operated, and the stone is worked into mortars, millstones, and troughs for milling grain, into arch work, and other constructional pieces.

METAMORPHIC ROCKS

Above Wei-chou, the silvery mica-quartz schist is removed in thin slabs and used for pavements around houses, in court yards, for stepping stones across wet places, and built up into walls along the road or around buildings. Earthen walls are common in the plains, but this flat-splitting schist makes a good substitute where soil is lacking. Many gneisses of excellent quality might be used, but they are not well situated for appreciative markets.

IGNEOUS ROCKS

Rhyolites.—The gneisses might have been placed under this heading, for they are all of igneous origin. The rhyolites near the Niang-tsu-ling Pass weather into a soft plastic clay and are worked far up the slope, as well as in pits below the road. The rotten stone is dug out, ground or pugged to a soft, easily worked, clay-like substance. It is carried out, moulded into pipe bowl, and burned, in preparation for market. The choicest, smoothest clays are packed and sent to apothecaries to be sold as a cholera cure.

Granites and porphyries.—Beautiful granites and porphyries crop out in many masses, some of which are large enough to be workable. But, like the gneisses, their utilization is impractical at present.

GENERAL ROUGH STONE

In a youthful valley, with notable scarcity of forest, the natural building material is stone. Stone is exposed almost all the way; it has been broken out by weather, gravity, and stream, and one can find abundant firm stone of many kinds. Roads are paved with slabs of stone; in places, cobbles are laid, in patterns, in the roads and courts. Houses are built of stone without mortar and are roofed with large slabs of schist or thin-bedded sandstones, laid over the tops of the walls in almost horizontal position and partly supported by log beams. Wei-chou is wholly walled in and stands mostly on a stony alluvial fan. Its towers, temples, and gateways are of stone. Kuan-hsien and some villages are also surrounded by stone walls.

MINERALS

Coal, coke, and graphite.—Some 5 to 6 miles up the road above Kuan-hsien are three workable coal beds. The east, or first, one is about 3 feet thick; the middle one, of comparable thickness, and the west one, a little thicker. Beyond some scores of feet of sandstone, there is a fourth bed, 2 or 3 feet thick. In most beds, a heavy sandstone forms the roof and gives strength to the structure. The beds are almost perpendicular, and for that reason alone are difficult to work. Men mine them on an incline for 200 to 300 feet and carry coal out in baskets on head or shoulders, or pull it out in a basket on a sort of sled, by means of a harness over their shoulders or a cable over their foreheads (Fig. 5). Two coke plants operate near the thick beds in the first group, and the fourth bed has several ovens in one plant. Both coal and coke are loaded upon flat, raft-like boats and are started toward Chengtu and other cities on the plain.

Above Wei-chou, on the road to Li-fan, a good graphite schist is worked, and its high value makes economically possible its transportation on carry-poles to Chengtu for manufacture.

Gold.—Auriferous gravels are known below, and around, Wei-chou. They have been extensively worked by primitive methods with considerable success. Holes have been dug in these stream-laid gravels to a depth of 30 feet vertically, and deeper horizontally, into the banks. Hundreds of lesser holes were seen in all the gravel surfaces of this stream junction area. No one seems to know which stream brings down the gold, to say nothing of the ultimate bedrock ledges that supply it.

Copper.—Less than 25 miles northeast of Kuan-hsien, at Pai-shui-ho, copper has been smelted for many years. The chalcopyrite ore has been

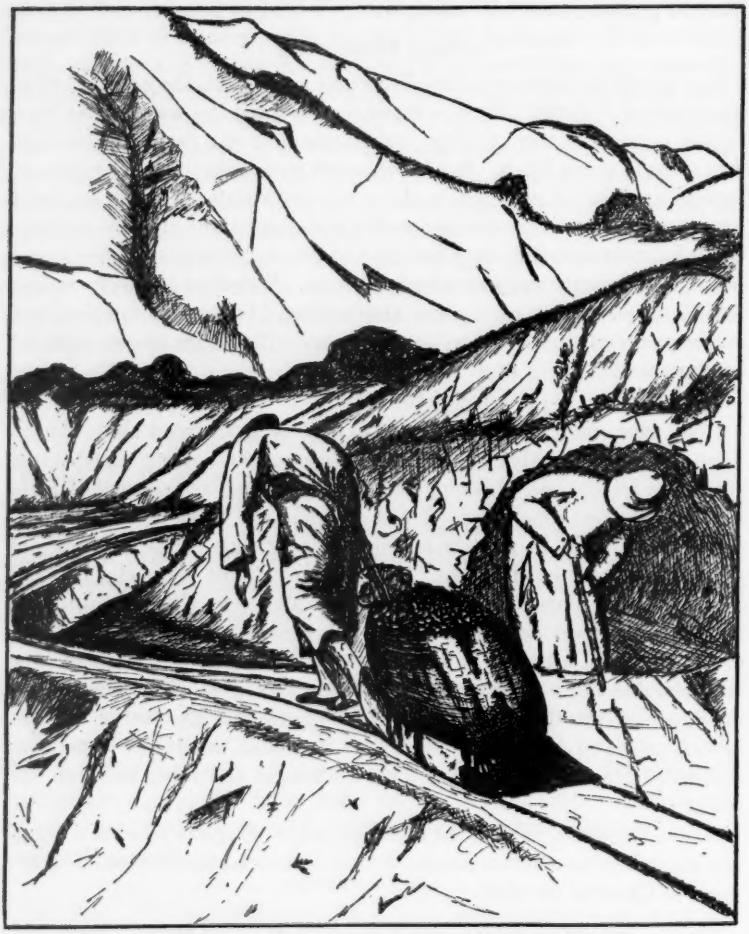

FIGURE 5.—*Miner with his load of coal (or shale) in a sled-basket*
He has just emerged from the mine into which the other man is looking.

mined for more than 200 years at Tung-ling-tsu, about 10 to 12 miles north of the smelter. From half a ton to one ton per day is taken out. Coal is mined about 3 miles south of the smelter. Charcoal and coke from the locality, as well as coal, are used in the smelters. These minerals, coal, and copper, in rocks striking from N 25° to 35° E, were seen en route from Chengtu to Kuan-hsien.

CONTRIBUTIONS OF THIS PAPER

The writer has attempted to bring together all known items, both of observed fact and of interpretation, and weld them into a single chapter. The weaving of all events into a chronological sequence is a second contribution, even though not all events can be dated as yet. Much assistance in actual dating has come from Chinese workers. The writer feels confident of the presence of a large geanticlinal structure, although it is neither so large nor so simple as it seemed in the field. The petrographic and petrologic studies, both megascopic and microscopic, have never before been attempted. Two periods and types of metamorphism are here recognized—the flow or pressure changes and the results of hydrothermal activity. Economic products are described for the first time. The correlation of late physiographic history into a sequence that emphasizes the youth of the present valley is the work of this study.

GEOLOGIC PROBLEMS

No reconnaissance survey should be completed without making an effort to recount the problems left for future study.

(1) Search for fossils in all strata that could possibly yield them.

(2) By means of fossils and other methods, more exact determination of the ages of the strata.

(3) A tracing of the structure along the strikes, with several purposes in mind: (a) to correlate with copper deposits known to the east; (b) to establish by correlation the true structural forms here; (c) to extend the search for fossils or correlate these beds with known fossiliferous horizons to east and west.

(4) Careful correlation of strata on opposite sides of the geanticline. This should follow an effort to test the theory that the Min River structure is an anticline.

(5) Thorough search for unconformities and faults and repetition of strata.

(6) Search for evidences of mineralization on contacts, with the purpose of finding economic resources as well as the extent of contact metamorphism.

(7) More exhaustive study of the auriferous gravels and a search for the sources of the gold.

(8) Measurement of all clastics, and detailed study of their petrology.

(9) Study of genesis of clastics.

(10) Study of known economic resources in the section—coal, marble, gold, pipeclay, and lime—to discover reserves and better ways of utilizing them.

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